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CORRELATION OF QUARTZ DEFORMATION WITH ITS CRYSTAL STRUCTURE

H. W. FAIRBAIRN, *Massachusetts Institute of Technology, Cambridge, Massachusetts*

ABSTRACT

Although it is well known that the manner in which a crystal deforms is governed by its structure, few correlations have been made. The results of an analysis of this type are given here for quartz and are summarized in Table 2. The table is incomplete in many respects and further investigation is required. The need for correlation studies of this kind in interpreting mineral orientation in tectonites is unquestioned and will serve to stabilize the tottering hypotheses used at present.

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INTRODUCTION

The task indicated by the title of this paper may seem futile to those familiar with the structure of silicates and with the structural relation which quartz bears to this group. It may likewise appear hopeless to others unfamiliar with silicate and quartz structures, but who recall from student days the conchoidal fracture and difficult cleavage of quartz. Neither point of view is entirely valid, however, for quartz shows a capacity to deform which is a revelation to those unacquainted with this phase of its behaviour. It is the purpose of this paper to correlate the scattered literature on quartz deformation and to expand the problem through a qualitative analysis of the structure. There is abundant evidence of different types of quartz deformation, all of which must eventually find their explanations in the crystal structure. The importance of this type of analysis is obvious in any petrotectonic analysis, since quartz has been the chief mineral studied, and it has long been apparent that interpretations were impeded by the lack of correlation with experimental and structural data. Griggs and Bell (1) have made a promising beginning in remedying this situation, and their contribution is well worth studying.

Types of Deformation

A summary of the different ways in which crystalline substances may deform when stressed beyond the elastic limit will help in the discussion of quartz deformation which follows. Beyond the elastic limit either *gliding* or *rupture* may occur. Gliding is a relative movement between certain sheets[1] of atoms which at no stage during the movement causes rupture of the structure. Rupture, on the other hand, arises from conditions which result in loss of continuity of the structure.

Gliding is of two principal kinds. Briefly, *twin-gliding* is a relative movement between two portions of a crystal which involves a change in mutual orientation of the two parts. The amount and kind of movement along neighboring gliding units necessary to bring about this change are governed by definite twinning laws. *Translation-gliding* is a relative movement between two portions of a crystal which does not involve a change in mutual orientation of the two parts. The amount of movement along neighboring gliding units is indefinite, although influenced strongly by the character of the crystal structure and its imperfections.

There are three types of rupture in crystalline substances. If a crystal breaks in such a way that its structure has little or no control over the form of the rupture, we call the break a *fracture*. If the form of the rupture is closely controlled by the structure, we designate it as *parting* and *cleavage*. Parting is a rupture on the composition plane between two twinned portions of a crystal. Cleavage is a structurally-controlled rupture which is independent of twinning.

In the following pages quartz will be analyzed in terms of these types of deformation. Although the treatment is most complete for cleavage and fracture, the problems connected with gliding are stated as fully as is consistent with the information available.

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[1] A sheet, as used here, comprises all the atoms between two successive, potential, glide-surfaces.

TWIN-GLIDING

The common quartz twins follow the Dauphiné and Brazil laws. In both, the vertical axis is the twin axis. The Dauphiné twin is composed of interpenetrating parts which are either all right-handed, or all left-handed, and cannot be identified by optical means. The Brazil twin is composed of interpenetrating right- and left-handed parts. A thick, basal section will show in its interference figure the phenomena of Airy's spirals. Except on basal sections, both types may be identified by suitable etching with HF, and usually consist of alternating rhombohedral lamellae, the orientation of the etch figure on alternating lamellae determining the twin law as Dauphiné or Brazil.

Experimental evidence of Dauphiné twinning has been obtained by Zinserling and Shubnikow (2) at room temperature and also near the inversion point. At the higher temperatures the twins formed under pressures as low as 1000 kg/cm^2. At lower temperatures they developed less easily. The authors consider quartz twinning to differ sharply from that represented by calcite twinning, but do not give an adequate interpretation. Twinning has not been thoroughly correlated with crystal structure for any mineral, and since it is not yet proven to be a factor in the formation of quartz tectonites, I have not attempted a correlation. Nothing would be gained by hazarding a correlation for a unique structure like that of quartz when the correlation for simpler structures has not yet been made.

The reason for development of Dauphiné or Brazil twins is a matter of some interest. The inversion of high-quartz to low-quartz results in a 2% decrease in volume, and in formation of irregular patches of Dauphiné twins. As this has the character of a deformation it may possibly be correlated with the Dauphiné twins produced by the Zinserling and Shubnikow experiments. Brazil twins are believed to be growth twins in quartz which have formed at temperatures below the inversion point. The rhombohedral lamellae forming the twins are commonly regular and extend throughout the whole crystal in contrast to the irregular, interrupted areas of Dauphiné twins.

Judd's opinion (3) from a study of a large twinned crystal runs counter to this idea. He found Brazil twins particularly well developed in those parts of a basal section which were highly fractured, and concluded that deformation was the chief factor in their formation.

The importance of twinning in the deformation of tectonite quartz is unknown. Neither Brazil nor Dauphiné twins can be identified optically in the ordinary thin section, and etching is rarely feasible because of the relatively fine grain. Sander has mentioned the possibility of twinning (4, p. 192, D.43) to explain the orientation of quartz in one example.

Although he has not directly stated the type of twin involved, it would necessarily be of the rare type represented by Japanese twins, in which the twin plane is a rhombohedral plane and the angle between the two vertical axes is 84° 33′. The evidence, however, is unconvincing and the orientation may be explained in other ways. Since there is experimental evidence that the commoner Dauphiné twin may be due to deformation, the problem should be explored further with respect to tectonites.

TRANSLATION-GLIDING

Muscovite—Translation-gliding has not yet been produced experimentally in quartz and it is advisable therefore to describe a related silicate structure in which translation does occur. All silicates are built up on the fundamental SiO_4 unit in which one Si atom is bonded to four O atoms in tetrahedral arrangement. Quartz is one of these SiO_4 structures. The various arrangements of these tetrahedra and their associated cations give rise to entirely different behaviour under deforming stresses.

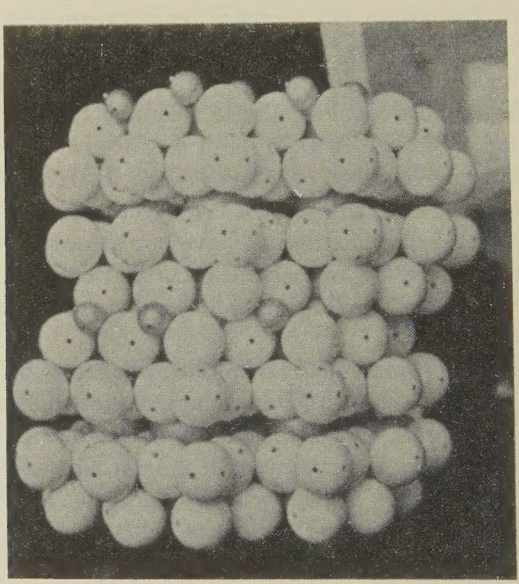

FIG. 1. Packing model of muscovite (14), looking approximately parallel to *b*. The linking of the SiO_4 tetrahedra to each other is clearly seen at the level in the structure where the small Al atoms lie. The absence of tetrahedral bonding at the level (locus of K atoms) where the bases of the tetrahedra face each other is also conspicuous. This is the translation and cleavage plane as explained in the text. The OH atoms (not seen in the photograph) are embedded between the tetrahedra at approximately the same level as Al. (Photo by William Parrish. Model constructed by Clifford Frondel.)

Silicates are distinguished structurally by the degree of sharing of the *O* of one tetrahedron with those of adjacent tetrahedra. In olivine, for example, none is shared, in pyroxene two are shared, in mica three are shared, in quartz all are shared. As will be seen, this distinction is of first importance in the production of gliding or rupture.

Taking muscovite as an example (Fig. 1), single layers of tetrahedra are linked together by *Al* atoms, forming a double sheet. The structure is a succession of these double sheets, placed so that the bases of the tetrahedra face each other. The double sheets are linked by *K* atoms.

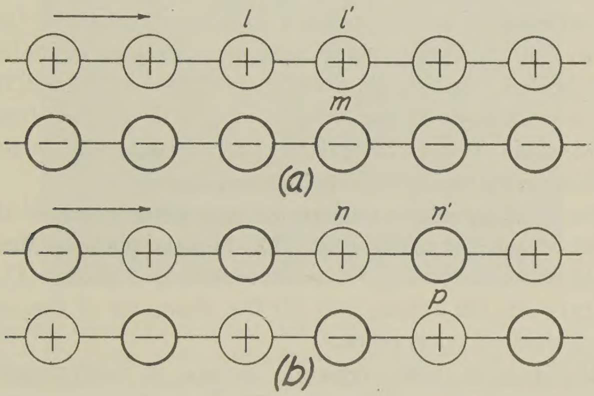

FIG. 2(*a*). To illustrate the essential feature of translation-gliding. The upper row of positive atoms can move over the lower row of negative atoms without development of rupture. Thus if *l* moves to *l*′, directly over *m*, the final disposition of atoms is identical with the original configuration. During the movement from *l* to *l*′ no unstable condition is approached, since the attractive forces between the adjacent unlike atoms maintain the continuity of the structure.

FIG. 2(*b*). To illustrate the essential feature of cleavage. The upper row of positive and negative atoms cannot move relative to the lower row of similar positive and negative atoms without development of rupture. Thus if *n* should move to *n*′, directly over *p*, the final disposition of atoms is unlike the original configuration. At the commencement of the movement from *n* to *n*′ an unstable condition develops because of the approach of *n* to a like atom *p*. Repulsive forces are thus set up which result in rupture.

In the following analysis of translation I am guided by the clear statement of its fundamentals given by Buerger (5).

The fundamental element of translation-gliding is the glide-line *t*. The glide plane is of secondary importance. The glide line is determined by the direction taken by rows of consecutive, like-charged atoms. Figure 2 shows the relation between two adjacent lines of atoms, in one of which gliding is possible, in the other impossible. The definition of gliding states that rupture does not occur at any stage of the relative movement. Thus at all positions in the gliding structure the forces of attraction must be stronger than the forces of repulsion. This condition is fulfilled for Fig. 2(*a*).

Possible glide-lines in muscovite (rows of consecutive, like-charged atoms) are to be found parallel to [100], [010], and [110]. These indices all refer to directions in the basal plane. In order, they are parallel to *b*, *a*, and the prism-base edge. Inspection of the model shown in Fig. 1 indicates that the gliding might occur between rows of *Al* and *O–OH* atoms, or between *K* and *O* atoms. Since large cations of low valence (e.g., *K*) have much weaker bonds than smaller ones of higher valence (e.g., *Al*), it is likely that the adjacent rows of *K-O* atoms will function as glide-lines in preference to the others. The order of preference for the possible glide-lines is probably [100], [110], [010], listed in order of increasing distance between equilibrium positions.

The plane *T* along which translation takes place is one of the zone of planes which contains the glide-line. The favoured plane is the one which has the least resistance to slip. Resistance to slip is due to (1) the bonding forces between the atoms, and (2) the character of the path along which the movement takes place.

The glide-plane, or more correctly, surface, is determined therefore only by proper evaluation of these factors. In a silicate structure it must first of all be one which does not break the tetrahedra, since there is greater resistance to gliding between *Si-O* atoms than between any other combination in the structure.[2] Since in muscovite three *O* in each tetrahedron are shared by neighboring tetrahedra, it is seen from Fig. 1 that the only possible glide-plane is parallel to [001], passing between the double sheets of linked tetrahedra.

These gliding elements were tested experimentally many years before it was possible to predict them from the structure. Mügge (6) determined the glide-lines [100] and [110] and glide-plane (001). From later petrofabric analyses Sander (4, p. 207 et seq.) also obtained indirect evidence of [100] and (001).

Quartz—The example of translation-gliding in muscovite is given in some detail in order to contrast it with quartz. In quartz the same tetrahedral arrangement of *Si* and *O* occurs, but, since every *O* in the tetrahedra is shared by a neighboring tetrahedron, there can be no sheet-like arrangement as in muscovite. The tetrahedra form a three-dimensional net, and since there are no weaker interstitial cations linked to *O*, the structure is bonded together very strongly and uniformly. Figure 3 shows a packing model constructed by Butler and Buerger which indicates something of the arrangement of the atoms. It is obvious from the *Si-O* relations described above that no glide-line is possible which does not break through one or more tetrahedral bonds. Thus translation-gliding, if it occurs at all, would be immensely more difficult to produce on the basis of the usual interpretation. Glide-lines might be expected, therefore, parallel to those rows of consecutive, like-charged atoms which produce the *minimum disturbance* of the tetrahedral bonds. Examination of the packing model of Fig. 3 shows that only one direction fulfills this requirement, and is parallel to the horizontal edges [*m*:*r*].[3]

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[2] Strength of bonding increases, in first approximation, with valence. *Si* is in most silicates the element with the highest valence, so that the *Si-O* tetrahedra are the most stable units.

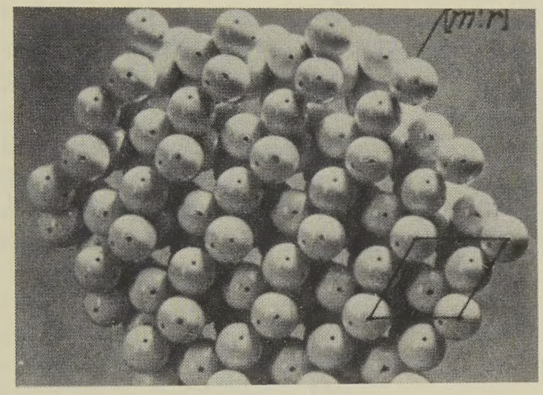

FIG. 3. Packing model of low-quartz (16) looking in the direction of the vertical axis. The *Si* atoms at the centers of the tetrahedra are not visible in the photograph. The sharing of each *O* between two tetrahedra is clearly seen, and emphasizes the great strength of the structure as compared with muscovite. The relative size of the model compared with a unit cell is shown by the parallelogram in the lower right corner. Line [*m* : *r*], lying in the plane of the photograph, shows the direction of a possible glide-line. The "holes" in the structure parallel to the vertical axis reflect a "columnar" bonding in this direction and are associated with a linear type of rupture as described in the text. (Model constructed by Butler and Buerger.)

[3] The nomenclature to describe the quartz planes referred to in this paper is as follows:

c is the basal pinacoid (0001)
m is the unit prism $(10\bar{1}0)$
a is the second-order prism $(11\bar{2}0)$
r is the positive rhombohedron $(10\bar{1}1)$
z is the negative rhombohedron $(01\bar{1}1)$
s is the second-order trigonal pyramid $(11\bar{2}1)$
x is the trigonal trapezohedron $(51\bar{6}1)$

The disposition of these planes on a right-handed crystal is shown in Fig. 4 (with the exception of *a* and *c*). *a* is uncommon as a crystal face, and *c* is unknown.

Directions in the lattice are referred to by combining the letters for two planes whose line of intersection represents this direction—thus, horizontal edges are [*m* : *r*] or [*m* : *c*], vertical edges are [*m* : *m*] or [*m* : *a*].

The attempt to assign a preferred glide-*plane* to it, however, would require more than a qualitative study such as is made here. Assuming that gliding can occur, it is quite possible that resistance to slip on all planes containing these horizontal edges is so great that a linear gliding alone occurs. In this case the glide-line would be the only element which controls the deformation.

There are no experimental data of translation-gliding in quartz. The statement in Sosman's memoir (7) that gliding takes place parallel to *m*, *r*, and *z* is not based on experimental evidence.[4] Griggs and Bell have surveyed the literature of quartz deformation in tectonites and find no unanimous opinion regarding translation-gliding. Possibly the wavy, high-refracting, parallel lamellae[5] in the quartz grains of many strongly deformed rocks may be caused in part by translation, but there is no proof as yet. These lamellae are uniformly sub-parallel to the base but do not have a fixed crystallographic orientation. Recrystallization obliterates all trace of them except in certain cases where they contain inclusions. No adequate explanation of their relation to the atomic structure is known at present.

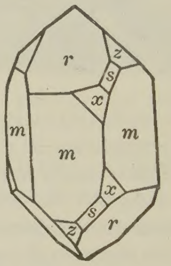

FIG. 4. Right-handed quartz crystal showing faces corresponding to the principal planes referred to in the text. (Reprinted by permission from "Textbook of Mineralogy" by Dana and Ford, published by John Wiley and Sons, Inc.)

RUPTURE

There is probably no crystalline solid whose rupture surfaces are not controlled, at least to some extent, by its structure. Strictly speaking, therefore, the terms cleavage and fracture have no precise meaning.

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[4] Written communication of Sosman to J. F. Bell.

[5] These lamellae are commonly referred to, erroneously in most cases, as Boehm lamellae. The original description by Boehm (see Griggs and Bell (1), p. 1726) refers to *lines of inclusions in recrystallized rocks* which may or may not be relicts of lamellae. They are most certainly unrelated to lamellae in those examples where they cross from one grain into another. Due to this confusion in use of the term "Boehm," I prefer to drop it entirely, except in a historical sense.

Common usage defines cleavage as a rupture which is closely controlled by the structure, and fracture as a rupture in which the structural control is weak. Since parting planes are dependent on a previously developed twinning, they do not show this gradation.

Figures 2(*a*) and 2(*b*) illustrate the contrasting conditions necessary to produce translation and cleavage. Fundamentally, the latter is a result of repulsion of like atoms when the relative movement between two lines of atoms tends to bring like atoms opposite one another.

Cleavage in Muscovite—The same example has been selected to contrast with quartz as was used to illustrate translation. There is a considerable literature dealing with the cleavage of minerals, and various rules have been formulated. The most recent and informative paper is that of Wooster (8), in which the various structural types are discussed in terms of their ability to cleave.

For silicates the following rules are given:

(1) The cleavage leaves the tetrahedra intact.

(2) In general, the cleavage exposes anions only (e.g. *O*, *OH*), but where no such plane exists, large cations (e.g., *K*, *Na*) may also be present.

(3) Where several cleavages are possible two cases arise—(*a*) If the distance between the anions in the different planes varies greatly, only the cleavages corresponding to the greatest distance will occur. (*b*) If the distances are nearly the same, they will all be cleavage planes.

Applying these rules to muscovite (Fig. 1), (1) the only plane which does not break the tetrahedra is parallel to (001), and is located at the level in the unit cell where the tetrahedra are back to back. (2) Cleavage in this plane exposes anions (*O*) and large cations (*K*). This plane corresponds to the excellent cleavage of mica. Although cleavage and translation follow the same plane in muscovite, this coincidence is not at all necessary.

Cleavage in Quartz—Strict application of the same set of rules to quartz fails. Since each *O* is shared by two tetrahedra, there is no plane in the structure which could leave these *Si-O* bonds intact should rupture occur. There would seem, therefore, to be no predictable cleavage in quartz. Since imperfect cleavages are well-established, however, the structure will now be examined for the most likely planes, and correlation attempted with the ruptures known to occur.

Figure 5 shows the edges of a series of planes of atoms parallel to *c*, *m*, *r*, and *a*. The arrows show the *Si-O* bonds, and also the positions of the atoms in each plane. These figures are for high-quartz and are thus simpler than the corresponding figures for low-quartz. For low-quartz the tetrahedra occupy slightly different positions which would complicate the figures without leading to any different conclusion.

These sets of planes have been selected because preliminary analysis

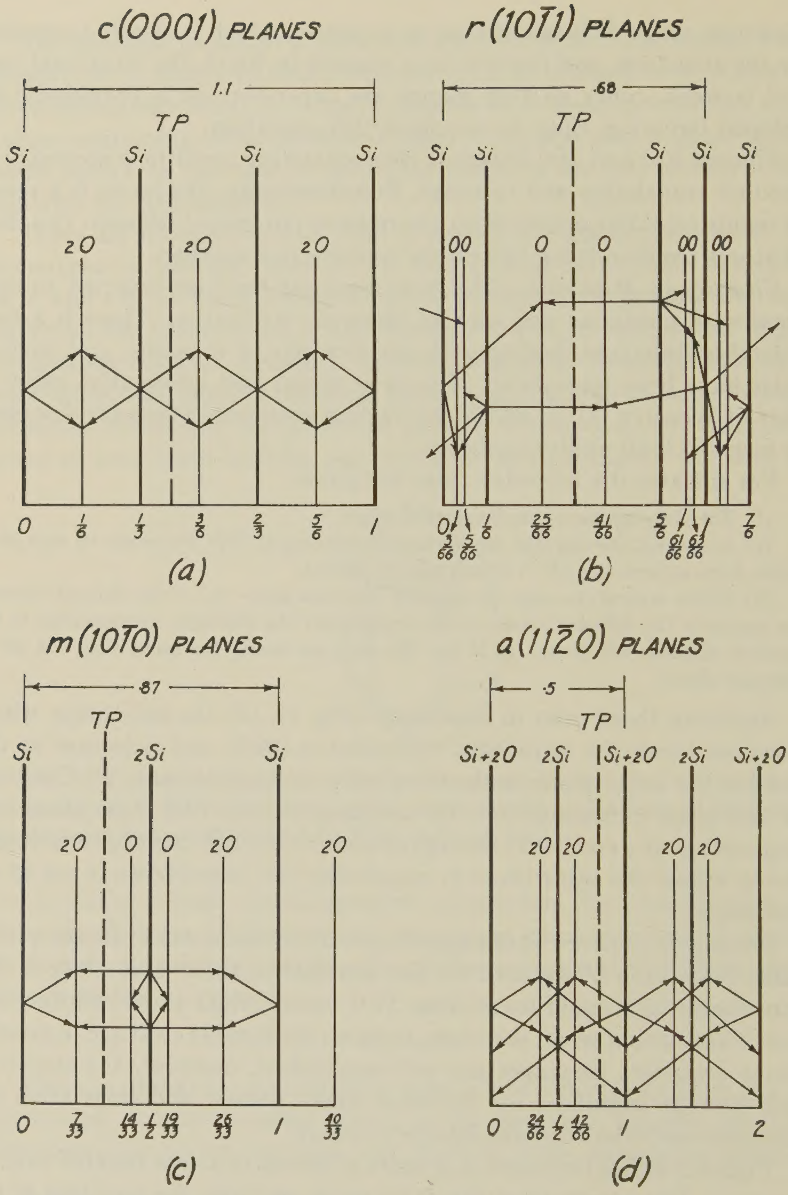

FIG. 5. Sets of atomic planes parallel to *c*, *r*, *m*, and *a*, as drawn for high-quartz by Niggli (13). Across the top of each set of planes is a number corresponding to an axial ratio in which each horizontal axis equals 1. The limits of a unit cell lie between 0 and 1, marked across the base of each set of planes. The positions of the SiO_4 units are shown by the bonding arrows. *TP* on each set of planes indicates a test plane for possible cleavage. The number of bonding arrows intersected by a test plane shows the unit rupture of tetrahedra for that position of the test plane. These planes are located to show the *minimum* rupture in each case. The four sets of atomic planes may then be directly compared as to cleavage possibilities.

showed that they offered the best prospects for cleavage. They are easily tested for cleavage possibilities by passing imaginary planes *TP* between adjacent atomic planes, noting the number of tetrahedral bonds which are intersected, and the number of *O* separated from each tetrahedron by this operation. The following table summarizes the results of such testing for those positions of the imaginary planes involving the least rupture of the bonds.

TABLE 1 (see Fig. 5)

I Plane series	II Area in sq. Å occupied by *TP* within limits of unit cell	III No. of tetrahedra broken per *TP*	IV No. of *O* broken from each tetrahedron	V Total *O* broken by each *TP*	VI Total *O* area of *TP* = bonding per sq. Å	VII % increase in bonding of *m*, *c*, *a*, over *r*, *z*
r	35.733	2	1	2	.056	
z	35.733	2	1	2	.056	
m	26.442	1	2	2	.076	36
c	24.040	1	2	2	.083	48
a	45.797	3	2 from one tetrahedron. 1 each from other two tetrahedra.	4	.087	55

Unit cell parameters $a=4.903$ Å, $c=5.393$ Å

Since ease of cleavage is dependent primarily on the bonding per sq. Å (for quartz the number of *O* broken from the tetrahedra per sq. Å), column V must be divided by column II for each set of planes. The result is tabulated in column VI and gives directly the relative ease of cleavage parallel to the planes considered. Column VII shows in per cent the increase in bonding for *m*, *c*, and *a* over *r* and *z*. It is obvious that the best cleavage should be parallel to *r* and *z*.[6]

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[6] A striking feature of the packing model of quartz is the occurrence of numerous sets of openings passing between the tetrahedra. The most conspicuous ones coincide with the horizontal edges [*r* : *m*], the rhombohedral edges [*r* : *r*] and [*r* : *z*], and the vertical edges [*m* : *m*]. The latter are the largest and are easily seen in Fig. 3. As far as known, these holes have no actual significance in an analysis of rupture, since the bonding would not be affected in any way if the tetrahedra were so oriented that these openings did not exist. It is significant, however, that the *r* planes contain more of these sets of openings than any other planes, indicating in a superficial way the weaker bonding already mentioned.

These calculations must not be used in a strictly quantitative sense, since factors such as the resolution of forces necessary to break the tetrahedra have not been taken into consideration. A precise quantitative study of this kind would be difficult for a structure such as quartz and is unnecessary for the problem at hand.

On the experimental side, considerable correlation is possible. Sosman (7) has summarized the older data. The positive rhombohedron *r* is conceded by all investigators to show the best cleavage. The negative rhombohedron *z* gives a poorer, but distinct, cleavage. Others reported are parallel to *m*, *c*, *a*, *s*, and *x*. Mallard (9) found that the rupture surfaces parallel to *m* and *c* were really composed of alternating *r* and *z* cleavages. Wright and Larsen (10) report on the abundance of rhombohedral ruptures in low-quartz which has passed through the high-low inversion point. In the preparation of thin sections rhombohedral cleavage may likewise develop in grains at the edges of the rock-slice.

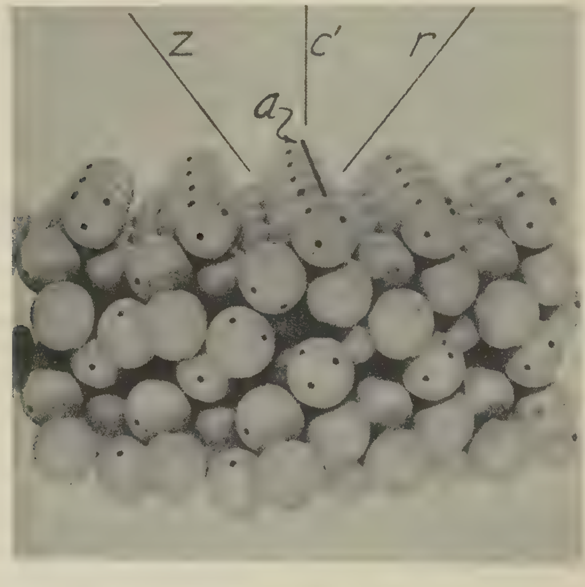

FIG. 6. Side view of quartz model of Fig. 3 tilted down at the front to give sufficient perspective. The close-knit, three-dimensional character of the structure is clearly seen in this view also; *a* is the line of strike of the rhombohedrons *r* and *z*, whose dips are indicated by the inclined lines. Although the identical bonding per sq. Å on these two planes cannot be seen from the figure, the greater "smoothness" of *r* as compared with *z* is easily appreciated from the arrangement of the *O* rows along the top of the model.

The superiority of *r* cleavage over *z* cleavage is probably due to the greater "smoothness" of the former planes. This is easily seen from Fig.

6, on which one rhombohedron of each type is marked for reference. Although the bonding is equal parallel to both surfaces, the *z* planes of atoms are not conspicuous in the figure. Close examination of the model reveals a very ragged surface. This inequality in the two rhombohedrons is probably one of degree, not of abundance, as the bonding strengths indicate an equal tendency to rupture. In high-quartz, having hexagonal symmetry, there is no difference in the "smoothness" of the pyramidal planes corresponding to the low-quartz rhombohedra. The pyramidal cleavages of high-quartz should be equally well developed. No experimental data are available to check this point.

Rupture parallel to *m*, composed of alternating *r* and *z* cleavages, as Mallard describes, should be easier to produce than ruptures of similar origin parallel to *c*. This is because the rhombohedral surfaces are more nearly parallel to the prism than they are to the base. The wide experience of the Japanese quartz workers seems to confirm this (11), as they have found that crystals are easiest to work on surfaces cut parallel to *c*. As an illustration, quartz vases are always hollowed out parallel to the vertical axis of the crystal, and engraving is also done on such sections.

Although a rupture of the type just described is very probable, there are at present too few observational data to warrant a statement that this is a general rule. Independent prismatic cleavage does occur, as shown by a crystal brought to my attention by Dr. Harry Berman.[7] This crystal is bounded on one side throughout its entire length of three inches by a fairly smooth cleavage face parallel to *m*. Structurally, however, there appear to be greater possibilities in this zone for a linear rupture than for the planar type observed in this crystal. The *m* and *a* prismatic planes give a total of six intersecting planes and, if *r* and *z* are included, six rhombohedral planes could also aid in the production of ruptures essentially parallel to the vertical axis. Participation of even a few of these twelve possible planes would give a linear character to the resulting composite rupture.[8] This may be the case in tectonite quartz showing parallel orientation of strain shadows under crossed nicols. These oriented shadows are seldom exactly parallel to the vertical axis and show irregularities within individual grains which point to an origin by rupture rather than by gliding.[9]

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[7] Specimen in Harvard Mineralogical Collection from Goyaz, Brazil.

[8] Since completion of the manuscript another example of prismatic cleavage has been described by Drugman (*Mineral. Mag.*, **25**, 259, 1939), in which three intersecting sets are shown in an excellent photograph. This illustrates the linear character of ruptures in the vertical zone.

[9] By certain writers these oriented shadows in tectonite quartz have been considered to represent translation-gliding. Griggs and Bell (1) have reviewed the printed evidence and find it inconclusive.

Ichikawa (11) reports imperfect ruptures parallel to *a*, *s*, and *x*, which may represent special combinations of rhombohedral ruptures. As already shown in table 1, *a* is less probable as an independent cleavage than *r*, *z*, *m*, and *c*, and it could be shown that *s* and *x* are even less probable. As a composite rupture, *a* might be explained as follows. Examination of any quartz crystal shows that *a* is symmetrically placed, and is sub-parallel, to two positive rhombohedrons at one end of the crystal, and to two negative rhombohedrons at the other end. Thus rupture parallel to all four rhombohedrons could result in a cleavage essentially parallel to *a*. However, as with *m*, independent cleavage can not yet be ruled out as a possibility.

The most recent experimental data on cleavage of quartz are given by Griggs and Bell (1). In a series of experiments performed on cylinders of differing orientation, immersed in Na_2CO_3 solution and subjected to 4000 atmospheres differential pressure at 400°C., it was found that the ruptured fragments took the form of needles. Measurement of the optic orientation of these needles showed further that the bounding faces were rhombohedral, prismatic, and basal, the predominating face depending on the orientation of the cylinder used. No estimate of the relative ease of separation parallel to these planes could be made from these particular experiments. The hypothesis of quartz orientation which Griggs and Bell have developed on the basis of these experiments will be discussed by me in a later paper.

Parting—Since parting is entirely dependent on the previous development of twins, it has importance in outlining the twin boundaries. As already pointed out, optical tests fail to indicate twinning in ordinary thin sections, and etching requires specially prepared material. Parting planes, where developed, are thus of great assistance. They represent rupture along planes whose atoms have been mutually rearranged by twinning, but, for reasons already stated for twin-gliding, no attempt is made here to correlate the crystal structure with the parting.

I know of no experimental evidence of parting planes developed in deformed quartz. In tectonites likewise they have not been reported to my knowledge. Some information is available, however, from veins and pegmatite dikes. Rogers (15) has described well developed parting parallel to the positive unit rhombohedron in vein quartz from California. It is never developed parallel to more than two rhombohedral directions in any one grain and is believed to be a result of the twinning produced by inversion. In pegmatite quartz from Sudbury, Ontario, I have seen grains composed of plates which probably are rhombohedral parting planes similar to those described by Rogers.

Parting planes parallel to other crystallographic planes have not been reported as far as I know. An interesting possibility which might be investigated concerns the *a* ruptures described by Mallard as cleavage. Parallel to this plane cleavage is less probable than for the unit forms, yet rupture was apparently easy to obtain. It is known that the twin plane for the Brazil law is *a* and, if *a* could also function as the composition plane under certain conditions, the *a* ruptures obtained by Mallard could be explained as parting planes.

TABLE 2. SUMMARY OF GLIDING AND RUPTURE IN QUARTZ[1]

Type of deformation	Predictable from structure	Experimental evidence
Twinning	Mechanism not investigated	Dauphiné twins
Translation	$t=[m:r]$ (possibly) $T=?$	No unquestioned data
Cleavage	*r*—best developed *z*—equally as abundant, but less perfect *m*—poorer than *r* or *z*, linear character *c*—slightly less probable than *m* *a*—slightly less probable than *c* *s* and *x*—improbable as independent cleavages	*r*—best developed *z*—less perfect *m* and *c*—poorer than *r* or *z*, may be composed of alternating *r* and *z* cleavages *a*, *s*, and *x* reported but may not be independent cleavages
Parting	Mechanism not investigated	None reported
Fracture	Best conchoidal fracture perpendicular to *m* —	Best conchoidal fracture perpendicular to *m* Unoriented fractures

[1] Quartz lamellae are not listed here as they have not been obtained experimentally and are not predictable from the structure.

Fracture—As already pointed out, even the most irregular fracture is probably controlled to some degree by the crystal structure it intersects. This is as true of quartz as of other minerals. Its conchoidal fracture, for example, is better known than the imperfect cleavages which have just been discussed. Even this fracture, however, has a vectorial character which is utilized by quartz sculptors (11). From long experience they know that conchoidal ruptures are much more regular perpendicular to the vertical axis than parallel to it, and spheres, for example, are always fashioned from a crystal by working in this way. The structural reason for the more regular fracturing perpendicular to the vertical axis is obvious from the preceding analysis of cleavage. Parallel to the vertical axis fracture would be splintery and probably interrupted by rhombohedral cleavages, since the unit rhombs are more nearly parallel to the vertical axis than to the base. Perpendicular to the vertical axis there is no linear cleavage and at best a very imperfect planar cleavage, so that there is less structural control of the fractures.

Sander (4, p. 311, D. 55) has described microscopic fractures in tectonites which pass through quartz grains *independently* of the orientation of the crystals. The fractures are straight, parallel, and are assumed to be tensional in origin. Many of the anomalous fractures obtained in experimental deformation are probably of this character. This is to be expected in a mineral whose structure is so closely-knit as that of quartz. Although I have been emphasizing the anisotropic side of its deformation in this analysis, isotropic deformation is not uncommon and interferes with the predicted anisotropic behavior.

INFLUENCE OF LINEAGE STRUCTURES

In the foregoing discussion the possible influence of crystal imperfections has not been considered. This was intentional, as I wished first to focus attention on the relation between the ideal quartz structure and its deformation. Deviations from predictable behaviour are not rare, however, and may be due to *lineage* structures. Buerger (12) has recently summarized much important data concerning such crystal imperfections and has discussed their influence on crystal behaviours. Crystals are, in general, imperfect, and are divided into branches, or lineages, which have slightly different orientations. The partitions between lineages are lineage boundaries. Under deformation these boundaries may act as gliding or rupture planes and their distribution and degree of disorientation may be controlling factors of the deformation. For example, the distance between successive glide planes in crystals is many times the distance between the planes parallel to which gliding should be possible. In an ideal crystal, however, in which there is uniform distribution of the stress, no one plane of atoms should have preference over another. Lineage structure could explain this anomaly through concentration of the movements in the boundaries. The slight disorientation of the lineages acts further as a brake on unlimited translation and is thought by Buerger to explain the "hardening" of metals brought about by cold-working.

Lineages are probably common in quartz, and are likely to have a longitudinal character parallel to the vertical axis (Fig. 7). Undeformed vein quartz showing "flamboyant" structure in thin section is possibly a manifestation of lineage structure. In tectonite quartz the rodded character of the strain shadows subparallel to the vertical axis may also be due primarily to lineages, altered by subsequent deformation. That is, in addition to purely structural reasons for rupture of quartz approximately parallel to the vertical axis, imperfections in the form of lineages possibly influence the spacing and ease of rupture in this zone. The interrelations involved here are beyond the scope of this paper. It is my purpose only to call renewed attention to lineage structure in quartz and to point out its possible significance.

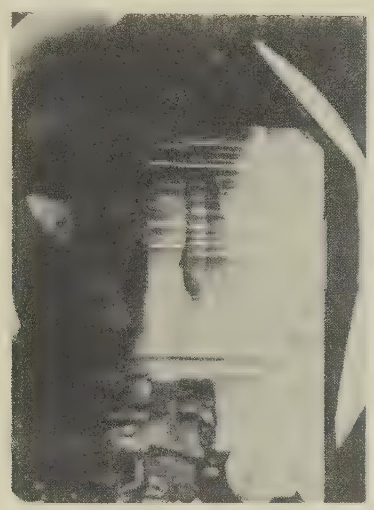

FIG. 7. Prismatic surface of a quartz crystal ($\times\frac{1}{3}$). The prism shows irregular elongate lineages approximately perpendicular to the horizontal oscillation striae. The orientation differences are exaggerated by use of oblique illumination. These disoriented branches, or lineages, may be important factors in certain types of quartz deformation. (Photo by Buerger.)

CONCLUSION

Although quartz has long been the despair of students of mineral deformation and is still more or less of an "enfant terrible," the foregoing analysis shows that its behaviour may be rationalized in terms of crystal structure, at least to some extent. There is essential agreement between experiment and prediction for most of the known cleavages and fractures; for parting, twinning, and translation the data are incomplete. Discrepancies may possibly find their explanation in lineage structures. In a succeeding paper quartz deformation in tectonites will be discussed in terms of possible hypotheses based on gliding and rupture. Although the present paper is admittedly qualitative, and therefore tentative only, its purpose will have been served if it stimulates criticism and further investigation.

ACKNOWLEDGMENTS

The inspiration to carry out this analysis of quartz was due primarily to the initiative of M. J. Buerger of this department in building packing models of various crystalline substances. The co-operation and assistance of Professor Buerger are gratefully acknowledged. J. F. Bell and W. J. Mead have given valuable advice from time to time and have criticized the finished paper. Other members of this department and of the Harvard Mineralogy department have likewise been helpful. To all of these I wish to express my appreciation.

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COLUSITE—ITS OCCURRENCE, PARAGENESIS AND GENETIC SIGNIFICANCE

Raymond Nelson, *Montana School of Mines, Butte, Montana*

Introduction

Considerable interest has been evinced, not only locally, but also in research laboratories outside of Butte, in the mineral "colusite," a sulfosalt of copper and tin. The present investigation is an outgrowth of apparent discrepancies observed to exist between published data and laboratory results obtained at Montana School of Mines.

Mr. Reno H. Sales, Chief Geologist of the Anaconda Copper Mining Company, first named the mineral, taking the name "colusite" from a claim, the Colusa, near which it was first found (2). Since its discovery on the 1200-foot level of the Leonard mine, colusite has been recognized on various levels of the West Colusa, Tramway, and Mountain View mines at Butte. In these mines it is valued only for its copper content, recovery of the tin being impractical under present metallurgical practice.

A preliminary study of the new mineral was made in 1922 by Mr. George G. Griswold, consulting metallurgist of Butte. In 1933 Landon and Mogilnor published a short general survey of colusite, including its formula, properties, and paragenetic relationship. Other than this material and a supplementary article concerning *x*-ray examination of the mineral (6), no descriptive literature concerning colusite exists.

Realizing that lack of laboratory *x*-ray equipment precluded a comprehensive study of the crystal structure and system, such work was left to others, our work being centered on:

1. Obtaining *pure* colusite for accurate determination of its chemical composition and specific gravity.
2. Observing its occurrence and associations, both underground and in polished sections, using iridescent-filming solutions as a tool in the latter work.
3. Incorporating these observations into an interpretation of the genetic significance of colusite.

Underground Occurrence

Sales (4) has mapped the Butte ore deposits in a zonal pattern consisting of: (1) a central copper zone, (2) an intermediate zinc zone, and (3) a peripheral manganese zone. It is not difficult to fit colusite in the broad geologic pattern outlined above. It has been observed in sizable amounts only in the central copper zone. It must be explained that minute inclusions of the mineral have been observed, microscopically, in ores from the Mountain Con and other mines bordering the central zone. Such inclusions are to be expected, as all the sulfide minerals commonly overlap from zone to zone. Colusite has been noted only in veins belonging to the Anaconda or east-west system, thus suggesting an age for the mineral that is coincidental with the earliest mineralization in the district.

Colusite is found almost entirely within the "horse tail" area, that "frayed out" structure that becomes evident on the eastward extension of the east-west system. This section of the vein system lies entirely within an area of intensely altered quartz-monzonite.

Sales has stated that "primary chalcocite and enargite occur only in association with the intensely altered granite [quartz monzonite] of the district" (4). Significantly, it is noted that colusite almost always occurs with either or both of these two minerals. Glassy quartz and pyrite, minerals generally regarded as having a high temperature of formation, were noted in abundance near exposures of colusite.

Colusite has not been noted above the 1200-foot level. Furthermore, downward extension of the tin-bearing sulfide is probable, colusite occurring throughout the zone from the 2800-foot to the 3000-foot level at the Tramway mine. The vein is not developed below that point in the colusite area.

In summation it may be said of the occurrence of colusite as determined by field studies: It is a primary mineral, occurring with minerals deposited under conditions of relatively high temperature; it probably resulted from primary ore deposition and it probably never reached the present outcrop. The available tonnage of the mineral is small in relation to that of other copper minerals.

Experimental Procedure

Through the cooperation of the Anaconda Copper Mining Company's geological staff, about 200 pounds of colusite-bearing ore was collected from stopes between the 2800-foot and 2900-foot levels of the Tramway mine, and from a vein in a 2800-foot-level drift at the West Colusa mine.

It soon became evident that segregation of pure colusite from associated impurities, the major one being enargite, would be impossible by ordinary hand picking, so efforts to purify the mineral were limited to:

1. Picking out idiomorphic crystals under a microscope.
2. Selectively floating colusite in flotation tests.

The picking operations resulted in two grams of colusite crystals being segregated. The specific gravity of this material was determined.

The flotation tests yielded two colusite concentrates. These were subsequently briquetted and examined under the microscope, grain counts being made. Knowing the percentages of impurities present and their respective compositions and specific gravities, it was a simple matter to calculate exact element-percentages for colusite and to determine an accurate specific gravity.

Flotation procedure for these tests can be summarized as follows: The ore, containing approximately 40% colusite, was comminuted to the flotation range, deslimed, and then subjected to a very gentle roast, drying on a hot plate to slightly inhibit all sulfides; actual flotation was accomplished using small quantities of pine oil and potassium xanthate, lime and potassium cyanide being added to inhibit pyrite, chalcocite and bornite.

It was found that colusite floated somewhat more readily than enargite, but not sufficiently faster to permit of rigorous separation of these two minerals. A grain count of the concentrate from Test No. 1 gave the following percentages: colusite, 86.1%; enargite, 12.2%; bornite, 0.6%; covellite, 1.1%. Concentrate No. 2 gave the following percentages: colusite, 88.4%; enargite, 9.9%; bornite, 0.3%; chalcocite, 1.4%.

MINERALOGY

Composition: The two concentrates were analyzed by chemists of the Anaconda Copper Mining Company, the composition of colusite being calculated on the basis of the known impurities as determined by the grain counts listed in the preceding paragraph.

Calculation sequence: (1) weight percentages of the mineral impurities were computed from the observed volumes, using specific gravities as given by Dana and Schneiderhöhn for the known minerals and using a specific gravity of 4.6 for colusite (see under specific gravity); (2) the impurity, SiO_2, was subtracted from the chemist's analysis and the weight percentages adjusted to the total amount of sulfides present; (3) amounts of copper, sulfur, iron, and arsenic sufficient to make up the known impurities were subtracted from the chemist's analysis; (4) remaining element percentages were attributed to colusite and were recast to a one hundred per cent basis.

The chemist's analyses of the concentrates and the calculated element percentages for colusite (Tramway Mine) are as follows:

	Colusite No. 1		Colusite No. 2	
	Analysis	Calculated	Analysis	Calculated
Sn	5.30%	6.18%	5.00%	5.68%
SiO_2	0.80		0.40	
S	26.50	25.83	28.55	28.41
As	8.90	7.77	8.80	7.92
Cu	49.22	49.47	48.67	48.28
Ag			1.32 oz.	
Au			0.01 oz.	
Sb	0.43	0.50	0.51	0.58
Zn	None		None	
Fe	1.36	1.51	0.98	1.07
Unanalyzed balance	7.49	8.74	7.09	8.06
Total	100.00	100.00	100.00	100.00

It will be noted that the analyses are only partial, approximately 8.0% being unaccounted for. Analyses by other investigators indicate that vanadium and tellurium account for the bulk of this remainder.

Samples from three mines, the Leonard, Tramway, and West Colusa, representing the major part of all developed colusite, check consistently in content of important elements (2) (3), with the exception of the analysis by Gross (2). Accordingly, this analysis should be dropped.

Although there is general agreement between the various analyses, there is not absolute agreement. This is perhaps due to the fact that enargite constitutes a substantial impurity in what has been regarded as pure colusite. On the other hand, in view of the zonal structure of colusite, which is described below, it is unreasonable to expect absolute uniformity as between samples secured from different mines or in different samples from the same place. Actually it seems as if the elements unquestionably present in colusite include four; namely, copper, tin, arsenic, and sulfur. Minor quantities of vanadium, antimony and iron are present, probably in solid solution.

Preliminary attempts at the pyrosynthesis of colusite from copper, tin, arsenic and sulfur have resulted in the production of small quantities of colusite as determined by the similarity of their physical properties to those of colusite, i.e., color, hardness, isotropy, and by their identical reaction to the same filming bath used for colusite. Filming brought out a rudimentary banded structure.

Specific Gravity: The specific gravity of this concentrate, recalculated on the basis of known impurities, is 4.58 when a water-pycnometer method is used. This may be compared with a specific gravity of 4.45 obtained with a water-pycnometer on the colusite crystals previously mentioned. It would then seem that the specific gravity lies within the range of 4.4 to 4.6.

Substitution of acetone and amyl alcohol for water as the liquid medium in pycnometer measurements resulted in complete elimination of buoyant air bubbles. Specific gravity results, however, were discordant, the values obtained ranging from 4.6 to 4.9. Such discordance appeared due to high coefficients of expansion and volatilities of these liquids. Likelihood of a specific gravity lower than 4.6 appears improbable.

Other Properties: Other properties observed in hundreds of examinations of colusite are: color, steel-gray bronze (megascopic) and creamy tan (in polished section); hardness, 3+ in Mohs' scale, being harder than enargite and so brittle as to be easily pulverized; cleavage, none; fracture, uneven to hackly (see Fig. 1); lustre, metallic, with a reflectivity of the order of magnitude of that of galena or chalcopyrite; streak, sooty-black like enargite. These check consistently with those found by Berman.

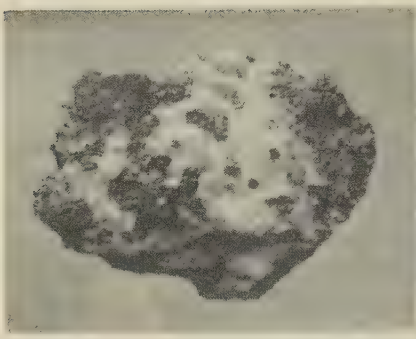
Colusite commonly occurs in complex aggregates of isometric crystals some of which are perhaps twins.

Structure: With the standard filming solutions described heretofore (1), colusite and enargite remain unaffected, though structure and paragenetic relationships of the other minerals are brought out. Therefore, a more potent filming solution was prepared as follows:

To 10 c.c. of a 50% (by weight) solution of chromium trioxide in water is added 10 c.c. of concentrated hydrochloric acid; this solution is stirred and allowed to cool to room temperature (18–20°C.).

Exposure of the polished section of colusite to this filming solution for 20 seconds develops in colusite an amazing banded structure, as may be seen from Figs. 3 and 4. The colors of the bands range from various shades of first-order tans and browns in 15 seconds, to beautiful first-order blues and hiatus yellows in 30 seconds. Marked contrasts of first-order browns and blues may be obtained by immersion of 20 seconds. Duplication of this color range, using longer periods of immersion, may be obtained by decreasing the strength of the chromium trioxide solution, e.g., 10 c.c. 30% CrO_3+6.4 c.c. HCl gives tan bands in one minute to various shades of blue and yellow in 3 minutes.

The banded structure is explainable only by postulating that the crystals grew in such a way that different layers had a somewhat different composition and that these layers of solid-solution oscillated about an average composition. This average composition is all that can be determined by chemical analysis.



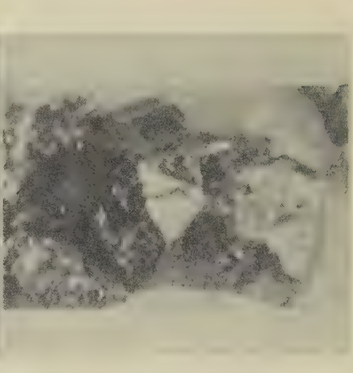
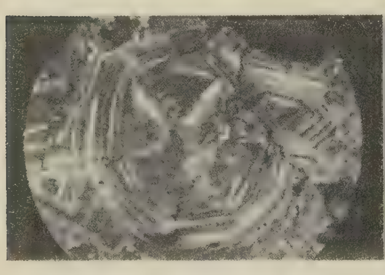


FIG. 1. Colusite with quartz. Note the hackly fracture, ($\frac{1}{2}$×).
FIG. 2. Broken crystal aggregate of colusite showing crystal faces, (4×).



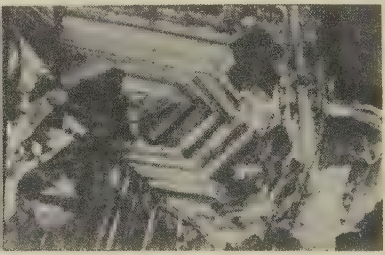
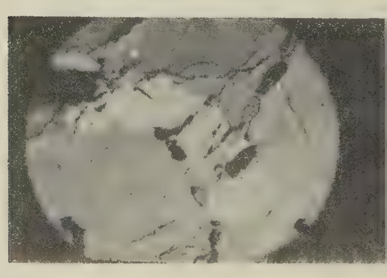


FIG. 3. Polished section showing zoning in colusite. Filmed two minutes in saturated solution of $CuSO_4 \cdot 5H_2O$ in HNO_3. Colors: first-order blues to second-order yellows, (50×).

FIG. 4. An enlargement of the above specimen showing the geometric arrangement and varied width of the bands, (100×).



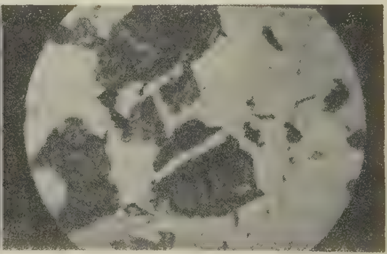


FIG. 5. Colusite (gray) veined by enargite (white) which is, in turn, veined by bornite (gray, slightly darker than colusite). Unfilmed, crossed nicols, oil immersion, (50×).

FIG. 6. Colusite areas observed in U.S.G.S. enargite specimen from Butte (Ref. No. 106). Note the enargite veins cutting across the banded structure of the colusite. Filmed 15 seconds in 10 cc. 50% CrO_3+10 cc. HCl. Colusite banded in tans and blues, (102×).

It must be strongly emphasized that these bands, as brought out by the filming solution, do not indicate a progressive change in chemical composition from center to edge, but rather pulsating changes in composition as the crystals grew. These growth rings vary in width as may be seen in Fig. 3 and, furthermore, their cycles of deposition must have been interrupted by frequent and extensive shattering and cementation, some banded segments being faulted and broken with new bands enclosing the whole. The colusite crystal represented in Fig. 3 has a center distorted and otherwise complicated by such diastrophism, yet the outer bands have a geometric simplicity that indicates lack of diastrophism.

If this banding represents differences in composition, it should be possible to homogenize them by heating the specimen to some temperature below the melting point. Attempts at such a homogenization were made using various oil baths at temperatures up to 400°C., and for times as long as four hours. Appreciable differences in the banded structure did not occur, some higher temperature being necessary to effect the change. Therefore, it seems likely that the mineral could withstand relatively high vein temperatures subsequent to formation and still retain its complex structure. It is significant that similar banding in tetrahedrite did become partially homogenized when subjected to a similar treatment, the filmed color becoming uniform with the bands remaining as a ghost pattern.

PARAGENESIS

Colusite was deposited with the older generation of sulfides and sulfosalts closely following the quartz-pyrite stage of deposition. With few exceptions it occurs in close association with enargite. When the polished surface is unfilmed it is impossible to decide which is earlier. However, iridescent filming brings out the fact that colusite is antecedent to enargite. Enargite veins frequently cut squarely across the banded colusite as may be seen in Fig. 6. Such evidence is most conclusive when the continuity of the same colusite band can be established on both sides of the enargite vein, as it is there. In other instances, colusite crystals have been stoped along some less resistant bands, and are now enveloped by enargite.

Bornite, chalcocite and chalcopyrite are definitely later than colusite, always filling cracks or fissures in the latter mineral. These veins occasionally contain inclusions of pyrite, which probably are the remnants of an earlier pyrite filling which had been replaced, as suggested by Landon, or else the stoped remnants of an early pyrite which had been carried in by fluid movement during the vein-forming stage.

Both enargite and colusite are veined by tetrahedrite-tennantite, this veining antedating that of the bornite-chalcocite as is shown by the cutting of the tetrahedrite veins by more recent veining.

In respect to the minerals observed together in the present investigation the sequence of deposition of sulfides was as follows:

(1) Pyrite
(2) Colusite
(3) Enargite
(4) Tennantite-Tetrahedrite
(5) Chalcocite and Bornite

Colusite is not an exclusive Butte mineral. The author observed its occurrence with enargite in U.S.G.S. specimen: Nat. Museum No. 81,127, from Red Mountain, Colorado. Further observation will doubtless disclose other occurrences.

Acknowledgments

The writer wishes to acknowledge the splendid cooperation he received from the Geological and Operating Departments of the Anaconda Copper Mining Company and specifically to thank Mr. Murl H. Gidel, Mr. Edward P. Shea, and their associates of the Geological Staff. Pertinent data gathered through years of underground observation were freely given.

The author also wishes to thank Professor A. M. Gaudin for the help and criticism he gave during both the research work and the writing of the manuscript. Thanks are also due Dr. E. S. Perry, Mr. John C. Rabbitt, and Dr. George Seager of the Montana School of Mines staff.

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RE-EXAMINATION OF COLUSITE

Harry Berman and F. A. Gonyer, *Harvard University, Cambridge, Massachusetts*

Colusite was named by Mr. Reno H. Sales, Chief Geologist of the Anaconda Copper Mining Company, a number of years before the mineral was studied in detail by Landon and Mogilnor (1933), and by Zachariasen (1933).* Somewhat earlier Schneiderhöhn and Ramdohr (1931) had referred the mineral to the tetrahedrite group, but without evidence. We have re-examined the mineral in this laboratory using well-authenticated material labelled *colusite*, which was collected a number of years ago by geologists associated with the Anaconda Company. A re-examination of the paragenesis of colusite has been undertaken by Nelson (p. 369, this journal) of the Montana School of Mines, in cooperation with the Anaconda Copper Mining Company staff. Our manuscript was submitted to Mr. Nelson whose independent check of our results is contained in his paper.

Crystals have been measured; an analysis of material has been made on a sample first examined in polished section; and finally an *x*-ray study of the same material, together with a density determination, was made. We find that colusite is, as Schneiderhöhn and Ramdohr have already hinted, a member of the tetrahedrite group, and that the unusual formula assigned to the material examined by Zachariasen is not applicable to our analysis. The material described by Landon and Mogilnor has the physical properties and apparently the general appearance of our colusite. However, the analysis given by them departs from ours, and the unit cell edge measured by Zachariasen is exactly half of our value. On the other hand, the partial analyses made in the laboratory of the Anaconda Company (by professional chemists), and quoted by Landon and Mogilnor, are essentially in agreement with our analysis, and consequently in complete disagreement with the analyses of Gross. Further, partial analyses, repeated by the Anaconda Company chemists (in Nelson's paper, this journal) verify our new analysis, and indicate that the material analyzed by Gross (in Landon and Mogilnor) was not representative of the composition of colusite. Therefore, on the basis of composition and physical properties, our material appears to be what was originally referred to as colusite, and some doubt must be cast on the samples examined by Landon and Mogilnor and by Zachariasen. This latter material may be a new mineral, but its properties are only in part those of colusite, in the sense of Sales, Schneiderhöhn and Ramdohr, Nelson, and ourselves.

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* The mineral was known to be tin-containing as early as 1917, in Professor Graton's laboratory at Harvard. Crystals were measured by Professor Palache and found to be tetrahedral. The investigation was, however, never completed.

The following is a description of what we believe to be colusite.

Crystallography: Isometric—hextetrahedral
Forms: *d*(011), *e*(012), *o*(111), *n*(112).

Figure 1 shows the average development of a crystal; all of the examined crystals show the tetrahedral development clearly, and leave no question concerning the crystal class. The habit of colusite is unique in that the tetrahexahedron *e*(012) is found in combination with the tetrahedron; careful study of Goldschmidt's Atlas revealed no tetrahedral mineral with this unusual combination. Other forms still unconfirmed because of their uncertain measurements are (001), $(1\bar{1}1)$, and $(1\bar{1}2)$. The crystallographic work was done by C. W. Wolfe.

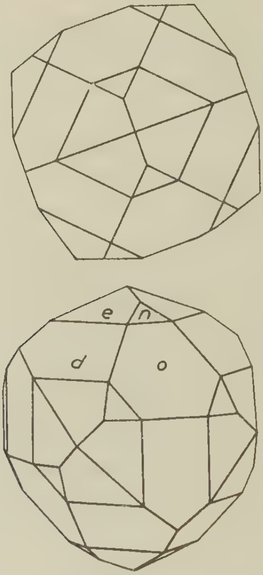

FIG. 1. Plan and elevation of typical crystal of colusite.

Structure cell: $a_0 = 10.60 \pm 0.01$ Å. The value here given was determined approximately, at first, on long exposures of crystals, using copper radiation and a rotating crystal, and later with more precision using the Weissenberg goniometer. The odd-order layer lines are weak and appear only after five hours (at about 40 KV and 10 MA; camera radius 28.65 mm.). A tennantite crystal examined in the same way showed a similar, but not so pronounced, weakness of the odd-order layer lines. (The cell edge given by Zachariasen is 5.304 ± 0.001 Å.)

Physical properties: Cleavage none. Brittle. H = 3–4. G. = 4.50, 4.434 calculated. Metallic luster. Color bronze. Streak black. Opaque. Isotropic in polished section.

The following etch reactions on a polished section by Esper S. Larsen, 3d, on the sample analyzed, establish the close relationship between our material and the other members of the tetrahedrite group.

Color—Coppery cream
Hardness—C+ or D−, Talmadge scale.
HNO_3—Stains differentially in brown, bringing out a zoned structure. Often negative within the ordinary time limit because of the slow start of the reaction.
HCl—neg.
KCN—brings out scratches. No discoloration.
$FeCl_3$—neg.
KOH—neg.
Aqua Regia—negative for 1 minute.

These etch reactions differ in some respects from those of Landon and Mogilnor, and are, therefore, another indication that the material of the two investigations was probably not identical.

The specific gravity given by Landon and Mogilnor is 4.2. Our density value, 4.50, was determined (using a micro-balance yielding values in general well within one per cent accuracy) on the same crystals as were used for the crystallographic and *x*-ray work.

Chemistry: The sample for analysis was chosen from the specimen containing the crystals measured. No important amounts of any other sulphide mineral were noted in the hand specimen, and the associated quartz was easily eliminated by separation in heavy solutions. The purity of the analyzed sample was determined by examination of part of the prepared material in polished section. A grain count (by Esper S. Larsen, 3d) gave: colusite 94 per cent, chalcopyrite and pyrite $\frac{3}{4}$ per cent, a white undetermined mineral $5\frac{1}{4}$ per cent. In the following table the analysis is given:

TABLE 1. ANALYSIS OF COLUSITE

	1	2		3	4
Cu	47.99	.7549 = 24×.0315		24.52	47.67
Fe	1.09	.0195	.2610 = 8×.0326	0.63	1.05
Sn	6.71	.0565		1.84	6.45
V	2.28	.0448		1.46	2.20
Te	1.26	.0099		0.32	1.21
Sb	0.19	.0016		0.05	0.19
As	9.54	.1287		4.14	9.18
S	30.65	.9560 = 32×.0299		31.06	32.05
	99.71				100.00
G	4.50				(calc.) 4.434

1. Colusite, Butte. Specimen number 92255. Analysis by F. A. Gonyer, on 0.8 gms.
2. Molecular proportions.
3. Number of atoms in the unit cell of $M_0 = 3248.5$ = molecular weight of the unit cell derived from x-ray data and density.
4. Calculated composition for the formula $8Cu_3(As, Sn, V, Fe, Te)S_4$ with As:Sn:V:Fe:Te as given in the analysis.

In Table 2 are given the previously published analyses of colusite, together with our analysis. Striking differences are shown, particularly in the presence of vanadium in our analysis, and the large amount of iron and considerable percentage of molybdenum in the analysis by Gross. The early Anaconda Company analysis (columns 1 and 2 of Table 2) and the newer partial analysis by the Company chemists (in Nelson, p. 369 of this journal) are essentially in agreement with our analysis.

TABLE 2. COLLECTED ANALYSES OF COLUSITE

	1	2	3	4
Cu	48.0	46.9	35.82	47.99
Fe	?	3.6	18.37	1.09
Zn	0.0	0.9	0.90	
Sn	6.9	5.8	6.64	6.71
Mo			8.80	
V				2.28
Te	3.0	0.4	2.97	1.26
Sb	2.6	0.64	0.58	0.19
As	6.8	8.4	2.50	9.54
S	27.5	29.2	24.20	30.65
	94.8	95.84	100.78	99.71
G			4.2	4.50

1. Leonard mine. In Landon and Mogilnor. Bi 0.0, Anaconda Copper Mining Co., Geological Dept.
2. Mountain View mine. Anaconda Copper Mining Co., anal.
3. Tramway mine. S. T. Gross, anal., in Landon and Mogilnor. Av. of 2 analyses.
4. F. A. Gonyer, anal. Harvard no. 92255. Analysis sample 0.8 gms.

On the basis of the chemistry of the tetrahedrite group as established by Kretschmer (1910) and by Wherry and Foshag (1921), and from structural studies by Machatschki (1928) and by Pauling and Newman (1934), the generally accepted formula may be expressed as follows:

$$A_{12}B_4S_{13}$$

with $A = \mathrm{Cu, Fe, Zn, Ag}$, etc.
$B = \mathrm{As, Sb, Bi}$, principally.

Our formula for colusite (for half the cell contents) is

$$\mathrm{Cu_{12}(As, Sn, V, Te, Fe)_4S_{16}}.$$

The colusite composition corresponds to the tetrahedrite requirement in an important respect, namely, that the ratio of $\mathrm{Cu : As+Sn+V+Te+Fe} = 3:1$. In addition, the unit cell content in both instances is approximately the same. The excess of sulphur atoms in colusite over that ascribed to the tetrahedrite minerals is not a serious discrepancy since the structural studies indicate the probability that vacant positions could readily accommodate extra sulphur atoms.

The close similarities between the sphalerite and tetrahedrite groups in their crystallographic, structural and chemical properties have been repeatedly noted. It is not surprising, therefore, that colusite has been placed previously in the sphalerite group. But no members of the sphalerite group have the large unit cell found by us for colusite, nor any considerable amount of arsenic (and similar kinds of atoms) in their composition.

Germanite has been placed tentatively by de Jong (1930) in the sphalerite group. Its composition can, however, be expressed as

$$\mathrm{Cu_{12}(Ge, Ga, Fe, Zn)_4(S, As)_{16}}$$

and this mineral may also well be a member of the tetrahedrite group.

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OCCURRENCE OF RIEBECKITE IN THE MICHIPICOTEN DISTRICT, ONTARIO

M. H. Frohberg, *Edwards Cons. Mines, Ltd.,*
Lochalsh, Ontario, Canada

Abstract

In reply to a recent paper by J. E. Hawley, evidence is presented according to which riebeckite occurs in the Michipicoten district as a hydrothermal alteration product, accompanying lamprophyre dikes. From these dikes the mineral was locally introduced into the gold-bearing and barren quartz veins, as well as other rocks cut by the lamprophyre intrusions. It is evident from these relations that the riebeckite was not associated with the gold-bearing solutions, since the period of gold deposition was separated from the formation of riebeckite by the intrusion of later dikes.

In a recent issue of this Journal, Professor J. E. Hawley[1] published a description of riebeckite from the Michipicoten district. As stated in the introduction to his paper, Hawley based his investigation on a number of specimens collected by Mr. O. A. Evans. It appears unfortunate, indeed, that Hawley had not had the opportunity of studying the occurrence of the mineral in the field, as his article contains erroneous inferences as regards the association and the origin of the Michipicoten riebeckite.

The present writer had observed the mineral during his activity in the Michipicoten district as mining engineer and geologist as early as 1928. In connection with his work for his doctor's thesis he determined the mineral as riebeckite on the basis of its optical characteristics and a qualitative analysis, and referred to it in two publications on the gold deposits of the same area.[2]

According to Hawley, riebeckite would appear to be an original though rare constituent of some quartz veins in the Michipicoten area. He states that "in the Michipicoten area, deep blue riebeckite is found in a few quartz veins and in both granitic intrusives and basic volcanics near the veins." Referring to the replacement of other constituents of the wall rocks of the quartz veins by riebeckite, he concludes as follows: "It would appear, therefore, that the riebeckite is one of the latest minerals to develop in both the veins and wall rocks."

Although riebeckite is quite frequently observed in the gold-bearing, as well as barren quartz veins, in the Michipicoten area, there is conclusive evidence that this mineral is not an original constituent of the quartz veins but is a hydrothermal alteration product accompanying lamprophyre dikes from which it was locally introduced into the quartz veins and their country rocks. This genetic relation is borne out by the fact that the mineral is rather common along the hydrothermally altered margins of the lamprophyre dikes which are considerably younger than the quartz veins. Gold mining operations in the district have yielded proof that riebeckite occurs in the lamprophyres, at considerable distances from the quartz veins, whereas its occurrence in the latter is invariably confined to places where such dikes intersect them. As the lamprophyre intrusions are the youngest rocks known in the area, riebeckite has been found in practically all rocks traversed by them.

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[1] Hawley, J. E., Riebeckite in quartz veins from the Michipicoten district, Ontario: *Am. Mineral.*, **22**, 1099–1103 (1937).

[2] Frohberg, M. H., Beiträge zur Kenntnis der turmalinführenden Goldquarzgänge des Michipicoten Distriktes, Ontario: *Min. Petr. Mitt.*, **44** (5), 363 (1933).

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The relative age of the quartz veins and lamprophyre intrusions is illustrated in the following table:

TABLE OF FORMATIONS IN THE MICHIPICOTEN DISTRICT

QUARTERNARY	
Recent:	Alluvial deposits
Pleistocene:	Glacial drift and lake deposits
PRE-CAMBRIAN	
Keweenawan:	Lamprophyre dikes Red feldspar-carbonate veins Younger diabase dikes
Algoman:	Pegmatitic (barren) quartz veins Gold-bearing quartz veins Granite, granodiorite, diorite and related porphyries
Haileyburian:	Older diabase dikes
Timiskaming:	Dore series: conglomerates, greywacke, tuffs, arkose
Laurentian:	Granite, diorite, various porphyries
Keewatin:	Basic and acid volcanics (flows, tuffs, breccias, agglomerates) with local sedimentary material and iron formation

The Michipicoten lamprophyres are rather fine-grained rocks occurring in the form of dikes which vary from a few inches to over five feet in width. Gledhill[3] distinguished two types, a biotite-rich and an olivine-bearing variety which he classed with the picrite family. The primary mineral components listed by Gledhill include olivine, biotite, and magnetite. Other dikes studied by the writer under the microscope are made up essentially of biotite with some magnetite and apatite, and one dike encountered underground at the Parkhill mine, contains as much as 50% magnetite in coarse aggregates, with biotite, augite and rutile as additional constituents.

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[3] Gledhill, T. L., Michipicoten gold area: *Ont. Dept. Min., 36th Ann. Rept.*, pt. 2, 14 (1927).

Characteristic of most lamprophyre dikes is a marked decomposition of the original constituents. This alteration is not due to weathering but is the result of hydrothermal infiltrations which in many cases proceeded along the dike walls. This fact is readily borne out by the bleached appearance of the marginal portions of many dikes. The alteration products include fibrous hornblende, serpentine, chlorite, epidote, riebeckite and carbonate. The last named is the final and most important of the secondary minerals and in some dikes has almost completely replaced the earlier alteration products. Locally, some pyrite or chalcopyrite has been deposited along the dike walls during the late hydrothermal stage of the lamprophyre intrusions.

These processes were not confined to the lamprophyres but to a lesser degree affected also the wall rocks of the dikes. As a result, the country rock generally shows an increased amount of carbonate and a development of silicates similar to those observable in the lamprophyres, although there are considerable variations in different rocks. The lateral extent of the alteration rarely exceeds one foot, but exceptions were noted where cracks in the wall rock of the dikes had provided an easy access for the rising solutions. In several instances, riebeckite accompanied by carbonate was found in veinlets reaching as far as ten feet from a dike.

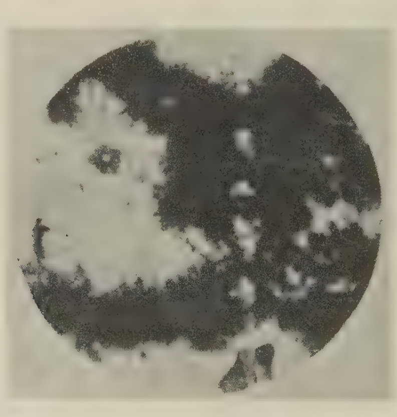

Fig. 1. Photomicrograph of a thin section showing riebeckite veinlets in gold-bearing quartz of the Parkhill Mine; riebeckite (black), carbonate (white, high relief), quartz (white, low relief). One nicol, ×60.

Owing to its blue color, the riebeckite is the most conspicuous of the various alteration products although it is, quantitatively speaking, of minor importance. Macroscopic aggregates generally occur in veinlets and cracks varying from a fraction of a millimeter to one centimeter in width (Fig. 1). The presence of microscopic needles of riebeckite can easily be detected by the bluish tinge of the altered rocks.

The Michipicoten riebeckite forms globular, botryoidal, and quite commonly almost earthy aggregates which consist of radiating or felt-like masses of minute fibers. As a rule, the individual fibers or needles are of microscopic size, although lengths up to three millimeters have been observed. The crystallographic habit of idioblastic needles is illustrated by Figs. 2 and 3. The color of the mineral ranges from deep blue to lavender and greyish-blue shades.

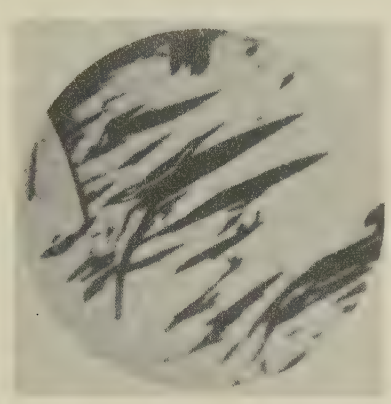

Fig. 2. Photomicrograph of a polished section of the Grace Vein, Darwin Mine, showing idioblastic crystals of riebeckite (black) in native gold (light-grey). One nicol, ×410.

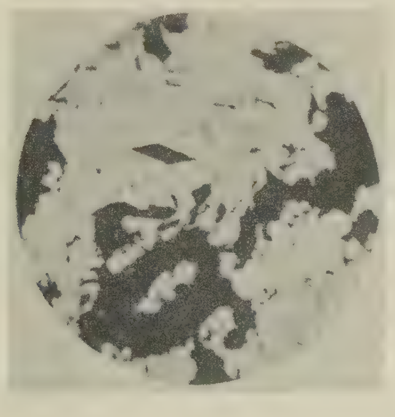

Fig. 3. Photomicrograph of a polished section of the Grace Vein, Darwin Mine, showing idioblastic crystals and veinlets of riebeckite (black) in native gold (light-grey) with inclusions of chalcopyrite (grey). One nicol, ×560.

In some thin sections of gold-bearing quartz traversed by veinlets carrying riebeckite, the latter appears to line the walls of the fracture, with idioblastic needles protruding outward into the quartz whereas carbonate makes up the center of the veinlet. Occasionally such veinlets carry also some epidote and pyrite. The epidote in nearly all cases shows signs of replacement by the riebeckite thus indicating its earlier age. Riebeckite and the carbonate appear to be essentially contemporaneous although a later carbonate generation distinctly replaces the riebeckite.

The age relations of the components of the veinlets are in accord with the observed sequence of the alteration products in the lamprophyres. Riebeckite appears to be invariably the latest of the newly formed silicates, as is evidenced by numerous examples of progressive replacement. As for the relations of the riebeckite to the sulphides deposited during the same hydrothermal stage, no conclusive evidence of a difference in age was ascertained, although in one case the writer observed what appeared to be a narrow veinlet of riebeckite extending a short distance into a pyrite aggregate. In places where the carbonatization of the lamprophyres has reached an advanced stage, remnants of riebeckite and of other silicates are found in the carbonate. The latter obviously corresponds to the second generation of carbonate observed occasionally in the riebeckite-bearing veinlets.

Wherever riebeckite is found in the wall rocks of the lamprophyre dikes its late age is borne out by a partial or complete replacement of the components of those rocks. As a rule, members of the ferro-magnesian group such as biotite, hornblende, chlorite and epidote appear to have been more readily replaced than other silicates. This seems to suggest that the iron contained in these minerals was used in the formation of the riebeckite molecule.

The age relations of the riebeckite to the late generation of native gold in the gold-bearing quartz veins is well illustrated in Figs. 2 and 3. These photomicrographs show idioblastic needles and veinlets of riebeckite in an aggregate of native gold which occurred in vein fragments within a wide lamprophyre dike cutting the Grace Vein at the Darwin Mine. In this case, the later age of the riebeckite was further proven by the fact that the riebeckite veinlets also cut red feldspar-carbonate veins[4] which traverse the gold-bearing quartz.

It is of interest to note that the association of the riebeckite with lamprophyre dikes is not confined to the Michipicoten district. In the Goudreau-Lochalsh gold area which is about 30 miles northeast of Michipicoten, the writer observed riebeckite in and near a lamprophyre dike which cuts the gold veins of the Edwards Mine. Also in this case, some riebeckite had been introduced into the gold-bearing quartz in the vicinity of the dike.

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[4] See table of formations.

ACKNOWLEDGMENTS

The writer is indebted to Dr. E. L. Bruce of Queen's University, and to Dr. G. M. Furnival, Lochalsh, Ont., for their helpful criticism, in connection with the preparation of this paper.

SALESITE, A NEW MINERAL FROM CHUQUICAMATA, CHILE

Charles Palache and O. W. Jarrell,
Harvard University, Cambridge, Mass.

Abstract

Salesite, $CuIO_3(OH)$, is a new mineral from Chuquicamata, Chile. Orthorhombic, $a:b:c=0.4442:1:0.6241$. Habit prismatic. Cell dimensions: $a_0=4.78$, $b_0=10.77$, $c_0=6.70$. Cleavage perfect $//\{110\}$. $H=3$, $D=4.77\pm.05$. Color green, $X=a$, 1.706, $Y=c$, 2.070 $Z=b$, 2.075, $r>v$, extreme, $2V=0$–$5°$. Biaxial negative. Analysis by F. A. Gonyer: CuO 30.62, Na_2O 0.59, I_2O_5 64.79, H_2O 3.68. Named in honor of Reno H. Sales, Chief Geologist of the Anaconda Copper Mining Company.

Salesite is an iodate of copper first found by the junior author in 1936 on the west side of Bench E-4 at the south end of the open pit at Chuquicamata, Chile. The only specimen found was an irregular bunch of crystals weighing about a gram. The only associated minerals are small amounts of quartz and kaolinized plagioclase, although the specimen was found in a part of the mine where atacamite is the most abundant copper mineral.

This specimen was sent to the Harvard Mineralogical Laboratory for further study, optical data having indicated that it was an undescribed species. It was overlooked in the collection until 1938 when Mr. Jarrell returned to Cambridge. He measured the optical characters more exactly, but the small amount of available material made exact determination seem hopeless. The crystal form was established as orthorhombic by the senior author, its specific gravity was determined and the presence of an excellent prismatic cleavage was established. It was only in a somewhat vague hope of gaining a qualitative knowledge of its chemical character that blow-pipe tests were made upon a few minute fragments. A closed tube test immediately showed the presence of iodine and a flame test proved that copper was present. With this knowledge a sample of about .3 gram was prepared and Mr. Gonyer made the analysis given below. It proved to be a basic copper iodate, $CuIO_3(OH)$.

The authors take great pleasure in naming this new mineral salesite in honor of Mr. Reno H. Sales, the well-known Chief Geologist of the Anaconda Copper Mining Company and its subsidiaries. Mr. Sales was responsible for pioneer work leading to the present knowledge of the geology at Chuquicamata and for recommending the drilling that in recent years developed the large reserves of deep sulphide ore.

Crystallography: Salesite is orthorhombic. It occurs in rather stout prismatic crystals with a pyramidal termination. Small crystals are of good quality and have the simple form shown in Fig. 1. The larger crystals show some rounding both of the prism zone and of the edge between prism and pyramid. The principal prism, parallel to which there is an excellent cleavage, is taken as unit prism and the terminal pyramid as unit pyramid. Three crystals were measured and gave the following fundamental angles:

			Range		No. of
	ϕ	ρ	ϕ	ρ	faces
110	66°03′	90°00′	65°50′–66°12′	——	9
111	66 03	56 57½	65°33 –66 27	56 50′–57 02′	8

From these angles elements were calculated, and the angle table that follows is based upon them.

Table 1. Angle Table of Salesite

Salesite—$CuIO_3(OH)$
Orthorhombic; dipyramidal—$2/m\ 2/m\ 2/m$
$a:b:c=0.4442:1:0.6241$; $p_0:q_0:r_0=1.4050:0.6241:1$
$q_1:r_1:p_1=0.4442:0.7117:1$; $r_2:p_2:q_2=1.6023:2.2512:1$

Forms		ϕ	$\rho=C$	ϕ_1	$\rho_1=A$	ϕ_2	$\rho_2=B$
c	001	—	0°00′	0°00′	90°00′	90°00′	90°00′
b	010	0°00′	90 00	90 00	90 00	—	0 00
n	130	36 53	90 00	90 00	53 07	0 00	36 53
m	110	66 03	90 00	90 00	23 57	0 00	66 03
e	023	0 00	22 35½	22 35½	90 00	90 00	67 24½
d	011	0 00	31 58	35 58	90 00	90 00	54 02
p	111	66 03	56 57½	31 58	40 00	35 26½	70 06½
(?) *r*	552	66 03	75 25	57 20½	27 49	15 53½	66 52

The form to which the symbol (552) has been assigned, which is shown as *r* in Fig. 2, is uncertain. It is rounded and the ρ angle varied through 4 or 5 degrees. It is, however, quite characteristic of the larger crystals. The domes *e* and *d* and the basal pinacoid shown in Fig. 2 are minute in size.

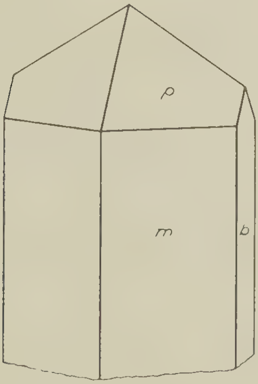

Fig. 1. Crystal of Salesite.

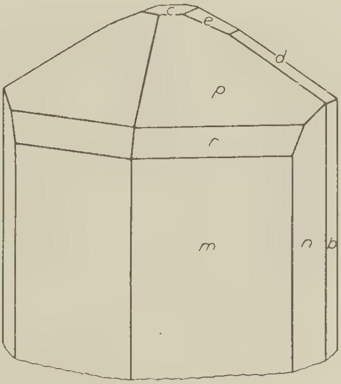

Fig. 2. Crystal of Salesite.

Physical Properties: Cleavage parallel to {110} very perfect. Specific gravity, determined with the micro-torsion balance on several grains that still, however, included some gangue, gave 4.77 ± 0.05. Hardness 3. Color bluish green, very similar to caledonite.

Optical Properties: The optical properties are presented in the following comparative table.

Table 2. Comparison between Salesite and Artificial Copper Iodate

	Salesite	Artificial basic copper iodate
Crystal system:	orthorhombic	orthorhombic
Orientation and Pleochroism:	X = a = colorless Y = c = light bluish green Z = b = bluish green	X = a = colorless Y = b = green Z = c = yellowish green
Cleavage:	{110}	{100}
α	1.786 ± 0.005	1.775 ± .01
β	2.070 ± .01	2.046 ± .005
γ	2.075 ± .01	2.052 ± .005
2V	0–5° (uniaxial for blue light)	0–5° (uniaxial for blue light)
Dispersion:	$r > v$, extreme	$r > v$, extreme
Optical sign:	biaxial negative	biaxial negative

Chemical Composition: Salesite is insoluble in water but is easily soluble in nitric acid. In the forceps, heated gradually, it darkens and yields a clear green flame of copper iodide. It does not appear to fuse. The residue left after heating on charcoal is readily reduced to metallic copper. In the closed tube, when first heated, it snaps into small splinters and almost at once gives copious purple fumes of iodine which crystallize on the wall of the tube. A small amount of water is also given off.

The chemical analysis was made by Mr. Gonyer on a sample of not more than 0.3 gram of material. For the water a separate sample of 0.11 gram was used. Regarding this determination Mr. Gonyer states: "The method by which the water of the copper iodate was determined is a modification of the Penfield 'Direct Method.' The water and iodine were driven off in a tube and weighed together. Potassium iodide was then used to dissolve the iodine and this solution titrated with sodium thiosulfate. The free iodine thus determined was deducted from the total weight of iodine and water, and the difference was assigned to water."

Table 3. Analysis of Salesite

	1	2	3	4	5
CuO	30.62	30.72	.3861	.3956	2.06
Na_2O	0.59	0.59	.0095		
I_2O_5	64.79	65.00	.1947	.1947	1
H_2O	3.68	3.69	.2050	.2050	1.068
	99.68	100.00			

1. Analysis of salesite by F. A. Gonyer.
2. Analysis recalculated to 100%.
3 and 4. Molecular proportions.
5. Simplified molecular ratio.

The figures of column 5 yield very exactly the formula $Cu_2I_2O_6(OH)_2$ or $CuIO_3(OH)$.

X-RAY STUDY OF SALESITE

W. E. Richmond

The *x*-ray determination of the lattice constants was made on a crystal approximately 0.5 millimeter in the elongation direction. Rotation, zero and first layer-line Weissenberg photographs about *b*[010] and rotation and zero layer-line photographs about *c*[001] were taken using CuK_α radiation. The measurements and calculations of these photographs give the following lattice constants.

$a_0 = 4.78$ $a_0:b_0:c_0 = 0.444:1:0.622$
$b_0 = 10.77$ $a:b:c = 0.44442:1:0.6241$ (morphologic)
$c_0 = 6.70$ $v_0 = 344.9$

The space group is D_{2h}^{16}—*Pcmn* derived from the following reflections on the Weissenberg photographs:

(hkl) = with all orders present
$(0kl)$ = with k even
$(h0l)$ = with $(h+l)$ even
$(hk0)$ = with all orders present

Content of the Unit Cell: The lattice constants together with the analysis by F. A. Gonyer and the specific gravity (4.77), give the unit cell content as shown in Table 4.

Table 4. Unit-Cell Content of Salesite

	1	2	3		4	5		6
CuO	30.72	31.14	0.3861	Cu	0.3861	3.85	4.04	4
Na_2O	0.59		0.0095	Na	0.0190	0.19		
I_2O_5	65.00	65.33	0.1947	I	0.3894	3.88		4
H_2O	3.69	3.53	0.2050	H	0.4100	4.08		4
	100.00	100.00		O	1.5751	15.71		16

Calculated density = 4.89
1. Analysis of salesite calculated to 100%.
2. Theoretical composition of $CuIO_3(OH)$.
3. Molecular proportions from column 1.
4. Atomic proportions.
5. Number of atoms in the unit cell.
6. Theoretical number of atoms in the unit cell.

The cell formula is therefore $4[CuIO_3(OH)]$.

Artificial Copper Iodate

Schulten (1904) described an iodate of copper with the formula $CuIO_3(OH)$, and gave the method of preparing it. This substance is orthorhombic with $a{:}b{:}c = 0.7124{:}1{:}1.7072$. It forms tabular crystals with $p\{001\}$, $g_1\{010\}$, $m\{110\}$ and $a_1\{101\}$ and has cleavage parallel to $\{100\}$. By a different setting of this crystal so that $c' = b$, $b' = c$, $a' = a$, the forms become: $g_1 = \{001\}$, $p = \{010\}$, $a_1 = \{110\}$ and $m = \{101\}$, and the cleavage is still $\{100\}$.

The elements for this position are:

	$a'{:}b'{:}c' = 0.4173{:}1{:}0.5859$
Salesite	$a{:}b{:}c = 0.4442{:}1{:}0.6241$

It is thus possible to bring these two substances into a relation with similar dimensions; but their cleavages are essentially unlike, pinacoidal in the one, prismatic in the other.

Mr. Gonyer made a solution following exactly the directions of Schulten and after about a week a crop of minute green crystals was obtained. These were measurable, and a prism gave the angle $m \wedge m' = 71°03'$, which is closely comparable to $m \wedge m' = 70°56'$ obtained by Schulten. Dr. Berman and the junior author studied these crystals optically and found that they agreed substantially in optical orientation with Schulten's data, so it was evident that we had the same substance as he had made. The optical properties of these crystals are, however, slightly different from those of salesite (see Table 2). Thus the two substances must be regarded as dimorphous since with the same composition they differ both in cleavage and optical properties.

No further attempt was made to reproduce salesite artificially, but after the first crop of the artificial copper iodate crystals was removed by Mr. Gonyer a second crop of blue crystals formed, which, however, were of a different salt, the triclinic hydrated cupric iodate.

Reference

Granger, A. and de Schulten, A., *Bull. Soc. Min. Fr.*, **27**, 137 (1904).

CALCAREOUS SHELLS REPLACED BY BEIDELLITE

Clarence S. Ross and Lloyd W. Stephenson,
U. S. Geological Survey, Washington, D. C.

Our knowledge of the mineralogy of clays has been making rapid advances in recent years, but much remains to be determined about the mode of occurrence and genesis, especially as it seems evident that the same mineral may form in various ways. For that reason the formation of an unusually pure clay mineral of the montmorillonite group by replacement of calcareous shells will, no doubt, be of interest.

The replacement of molluscan shells by clay material was first observed (by L. W. S.) in a railroad cut one-half mile south by west of Pontotoc, Mississippi, in 1910, and subsequent visits were made to the locality in 1915, 1936 and 1938.

The shells occur in the coarse-grained, yellowish-brown basal sand of the Clayton formation of the Midway group of Eocene age, which immediately overlies the Owl Creek formation of Upper Cretaceous age. The occurrence, stratigraphic position, and age have been described in the Journal of Paleontology,[1] and this was accompanied by a note on the character of the clay material. The fossil shells are in a good state of preservation, but are very soft and easily damaged. The clay contains a large proportion of excess water, which quickly evaporates on exposure to the air, and the shells shrink and shrivel into thin flaky fragments. Even when packed in damp sand, and allowed to dry slowly for nearly a year, the final state of preservation is very poor. The shells have been reworked and redeposited from an underlying Cretaceous bed which is not exposed in the immediate vicinity, but which must have been nearby, for the shells show little evidence of wear by transportation. Therefore, this transportation must have occurred before their replacement by fragile clay material.

The Clayton sand in which the shells occur is made up mainly of angular to sub-rounded grains of quartz that average about 0.35 of a millimeter in diameter but are variable in size. They are thinly coated with an admixture of highly ferruginous clay and limonite. That is, calcareous shells while enclosed among sand grains coated with a small proportion of iron rich material, were replaced by an extremely pure clay mineral.

The shells are dull olive-gray when moist, and gray to brownish-gray when dry. The material is unusually translucent and resembles horn when dry. The original structure of the shells is very perfectly preserved in the clay material. In one specimen the minute lamellae of the clay material average about 0.015 millimeter in width, but are sharply distinguishable by the different crystallographic orientation in adjoining areas. A material with a similar, but slightly coarser structure, is illustrated in the accompanying figure. No impurities of any kind were observable after obviously iron-stained material had been removed. The microscope reveals numerous areas where a uniform optical orientation of the clay material permits a determination of its optical properties. The mean index of refraction is about 1.53, which is a little high for minerals of the montmorillonite group, but is, no doubt, due to the iron content. The mineral is biaxial, negative, with a variable axial angle, and the birefringence is about 0.03.

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[1] Stephenson, L. W., Fossil mollusks preserved as clay replacements, near Pontotoc, Mississippi: *Jour. of Paleontology,* **13,** (no. 1), 96–99, pl. 16 (1939).

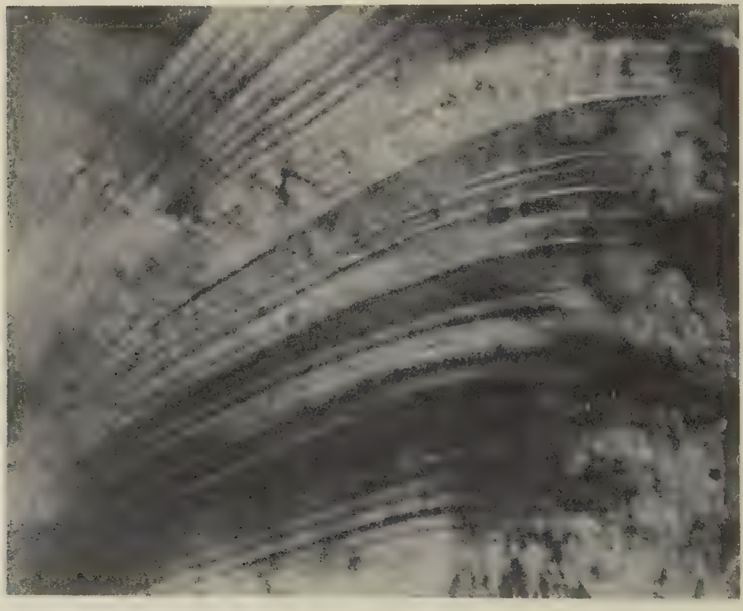

FIG. 1. Photomicrograph (×260) showing the fine structure of a fragment of a bivalve molluscan shell replaced by clay (beidellite). The photomicrograph was taken under crossed nicols, the structure being shown by a different optical orientation of the clay crystals in the different lamellae.

A sample was prepared for chemical analysis by scraping away the adhering sand grains and the iron stained portions. The results of a chemical analysis are given on opposite page.

Chemical Analysis of Pontotoc Clay Mineral

(J. G. Fairchild, analyst)

SiO_2	46.95
Al_2O_3	27.26
Fe_2O_3	2.26
FeO	0.32
MgO	1.39
CaO	None
Na_2O	0.20
K_2O	0.36
H_2O-	11.10
H_2O+	10.55
TiO_2	None
P_2O_5	0.03
MnO	0.01
	100.43

The chemical analysis shows that the mineral is the high aluminous beidellite member of the montmorillonite group.

The minerals of the montmorillonite group have a very complex composition which may be represented by several end members. Typical montmorillonite is represented by the following formula: $Al_2Si_4O_{10}(OH)_2$ or $Al_2O_3 \cdot 4SiO_2 \cdot H_2O + Aq$. It nearly always contains some proportion of the analogous nontronite molecule $Fe_2'''Si_4O_{10}(OH)_2$ or $Fe_2O_3 \cdot 4SiO_2 \cdot H_2O + Aq$. The magnesian end member is allied to the "bentonitic magnesian clay mineral" described by Foshag and Woodford,[2] $Mg_3Si_4O_{10}(OH)_2$ or $3MgO \cdot 4SiO_2 \cdot H_2O + Aq$, dimorphous with talc. In part, Al proxies Si in minerals of this group, but where this occurs a negative charge is induced, which must be neutralized by some other substitution. This is, no doubt, brought about in part by K, which forms a link between the sheets, giving the typical muscovite formula, $KAl_2AlSi_3O_{10}(OH)_2$ or $K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 2H_2O$.

The mica probably exists as an interstratification of muscovite and montmorillonite, giving a mixed-layer mineral as described by Gruner[3] for hydrobiotite.

A small part of the Na and perhaps even a little Ca may play the same role as K, but these elements have different ionic diameters and coordination numbers, and are very largely replaceable in the clays; and for the most part are probably not an essential part of the mineral.

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[2] Foshag, W. F., and Woodford, A. O., Bentonitic magnesian clay mineral from California: *Am. Mineral.*, **21,** 238–244 (1936).

[3] Gruner, John W., The structure of vermiculites and their collapse by dehydration: *Am. Mineral.*, **19,** 557–575 (1934).

The K, and indeed all the bases other than the Mg, nearly all of which proxies Al and so plays a very different role, are commonly inadequate to balance this negative charge. This balancing is believed to be brought about by OH taking the place of one of the O ions for each Al ion that replaces Si.[4] The resulting formula then becomes $Al_2AlSi_3O_9(OH)_3$ or $3Al_2O_3 \cdot 6SiO_2 \cdot 3H_2O + Aq$.

Small amounts of ferrous iron, no doubt, play the same role as Mg. The Pontotoc clay would then be composed of the following molecules, together with their proportions, recalculated to 100 per cent:

$Al_2Si_4O_{10}(OH)_2$	Montmorillonite	30
$Al_2AlSi_3O_9(OH)_3$	Beidellite	53
$Fe_2Si_4O_{10}(OH)_2$	Nontronite	7
$Mg_3Si_4O_{10}(OH)_2$	Hector clay	6
$KAl_2AlSi_3O_{10}(OH)_2$	Muscovite	4

Dehydration tests of the Pontotoc clay were made by P. G. Nutting of the United States Geological Survey, and these show that it contains about 8 per cent of H_2O, which is lost above 430°C., where there is a sudden break in the dehydration curve. Normal montmorillonites (those which approximate a 1:4 silica:alumina ratio) contain 4 to 4.5 per cent of water under the same conditions. This greater percentage of high-temperature H_2O tends to confirm the conclusion that the high-alumina clays should be higher in essential water. In fact, 8 per cent is a little too high, as a pure beidellite $[Al_2AlSi_3O_9(OH)_3]$ should, according to the theory, contain about 7.5 per cent of H_2O.

The replacement of calcareous shells by clay material raises a question as to the chemistry of the process. It is evident that clay forming material must have been introduced into the shells from the outside and solutions of some kind are the only means for such replacement. Clay is a material that, no doubt, is commonly transported in colloidal solutions, which have small power of penetration, and are ineffective for the removal of replaced material. It, therefore, seems probable that the calcareous shells from near Pontotoc were replaced by solutions carrying the necessary elements for the formation of clay in true chemical solution. These solutions dissolved and removed the $CaCO_3$ of the shells and at the same time were introducing Al_2O_3, SiO_2, a little Fe_2O_3, MgO, and unimportant amounts of other elements. In these sands there is no evidence of thermal solutions, and the transfer seems to have been due solely to those acting at normal earth temperatures. The clay mineral contains no CaO, although a small percentage is normally present in minerals of this group. This is surprising, as it shows the complete removal of CaO from the calcium carbonate of the shells.

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[4] Hendricks, Sterling B., Personal communication.

About 14 miles north of Pontotoc and 3¼ miles south of New Albany, there is a bed that contains abundant reworked Cretaceous shells and occupies the same position at the base of the Eocene. Here the shell bed is from 2 to 3 feet thick, and is a greenish-gray, sandy, coquina-like, friable limestone. The matrix between the shells contains abundant limonitic oolites, and a few spherical grains of calcite. The shells are for the most part calcium carbonate, but here and there the calcium carbonate has been partly replaced by clay material of the same type previously described.

NOTES AND NEWS

QUALITATIVE DETERMINATION OF FLUORINE IN MINERALS

Frank C. Foley and Philip W. West,
University of North Dakota, Grand Forks, North Dakota

A method for the quantitative determination of fluorine in samples of ground water from North Dakota,[1] which proved reliable for amounts of less than one part per million of fluorine, has also been used successfully for the qualitative determination of fluorine in minerals. In most cases the method is rapid and has proved effective when used by elementary students in mineral identification.

The procedure is a modification of the zirconium-alizarin colorimetric determination of fluorine in water[2,3] and depends on the fading of a zirconium-alizarin lake in the presence of fluorine. The pink color fades to yellow with the amount and speed of fading in direct proportion to the fluorine present.

Indicator

The zirconium-alizarin indicator is prepared as follows: (a) dissolve 0.17 gm. alizarin sodium sulphonate in 100 ml. distilled water; (b) dissolve 0.87 gm. zirconium nitrate in 100 ml. distilled water; add (a) to (b) slowly and with constant stirring. If kept in a cool, dark place the indicator is sensitive for about six months.

Procedure

Prepare a sodium carbonate bead in a platinum wire loop and fuse into it as much of the powdered mineral as is used in a normal bead test. Dissolve the bead in 1 ml. 1:1 hydrochloric acid in a test tube, then dilute to 5 ml. with distilled water. Add two drops of the indicator and mix. If fluorine is present the original pink color fades to yellow. As an aid in observing fading, particularly where fluorine is present in small quantity, prepare a blank of 1 ml. 1:1 hydrochloric acid diluted to 5 ml. as before and with two drops of indicator. By comparison with the blank, fading is usually seen in the test in two to three minutes though very small quantities may require as long as twenty minutes to show fading. In cases where fading is slight, it is more readily observed by looking directly into the test tube held above a white background.

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[1] Abbott, G. A., The fluoride content of North Dakota ground waters as related to the occurrence and distribution of mottled enamel: *N. Dak. Geol. Survey. Bull.* **9**, 1937.

[2] Thompson, T. G., and Taylor, H. J., *Ind. Eng. Chem., Anal. Ed.*, **5**, 8709 (1933).

[3] Sanchis, J. M., *ibid.*, **6**, 134–135 (1934).

INTERFERING SUBSTANCES

It was found that large amounts of phosphates, sulphates, arsenates and sulphides cause some fading of the lake. The latter two may be removed by roasting and sulphates by precipitation with barium chloride and filtering through fluorine-free filter paper. No satisfactory method of removing phosphate is known except distillation.

In cases where phosphates are present, or where traces of fluorine must be detected in the presence of large amounts of interfering substances, a Willard-Winter distillation[4] is recommended with a fluorine test made on the distillate.

Fuse 2 or 3 gm. of finely powdered material to be tested with sodium carbonate. Dissolve the fused material in 50 ml. 1:1 sulphuric acid in a 125 ml. distilling flask set up as shown in Fig. 1. Heat until the temperature reaches 140°C., then hold at that temperature by admitting small amounts of distilled water from the dropping funnel. When 50 ml. of distillate have been caught, remove any sulphate that may have come over during distillation, make alkaline with ammonium hydroxide and concentrate to about 4 ml. Neutralize with 1:1 hydrochloric acid, then add 1 ml. excess. Add two drops of indicator and compare after fifteen minutes with a blank. By this procedure 0.05 mg. per liter may be detected easily. If the amount of fluorine is small, a quantitative estimation may be made by a comparison of the test with standards made from a standard sodium fluoride solution.

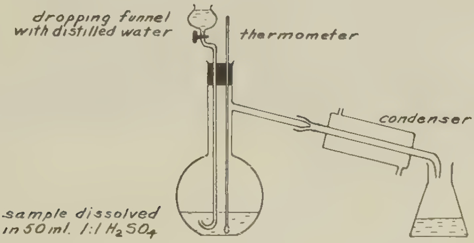

FIG. 1

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[4] Willard, H. H., and Winter, O. B., *Ind. Eng. Chem., Anal. Ed.*, **5**, 7 (1933).

A VERTICAL ILLUMINATOR FOR LOW MAGNIFICATION PHOTOGRAPHY OF POLISHED SURFACES

J. A. Legge, Jr.,
University of Arizona, Tucson, Arizona

The writer finds it desirable in many instances to photograph polished surfaces in their entirety rather than be restricted to a limited field provided by the reflecting microscope. This is particularly true where textural gradations cover a rather large area. To render detail effectively, vertical illumination is necessary in photographing polished sections at natural size, or with low magnification. For this purpose the author has designed a simple illuminator.

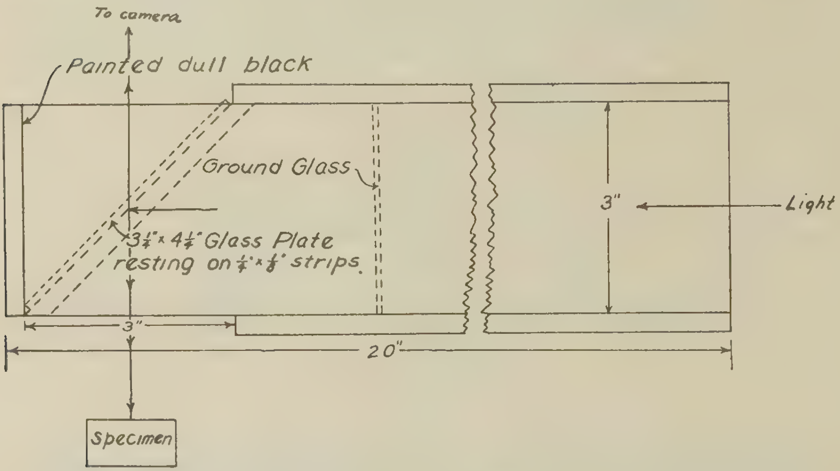

Fig. 1. Elevation of vertical illuminator.

The illuminator consists of a wooden tube 20 inches long, 3 inches high, and 3¼ inches wide, inside dimensions, closed at one end. At the closed end a space of 3 inches is left open on top and bottom. A glass plate is placed at an angle of 45° across the opening. The light coming from the open end of the tube is partially reflected and partially refracted. The reflected portion is directed vertically downward and is in turn reflected up the system by the specimen. Part of this reflected light strikes the lower side of the inclined glass plate and is reflected out through the wooden box, a small part is absorbed by the plate and the balance continues up through the camera.

The end of the tube is painted a dull black so as to absorb all the light refracted by the plate in its first reflection. Otherwise this light will reflect up the axis of the camera and cause a fog or haze on the film. The glass plate must be scrupulously clean to prevent hazing of the image.

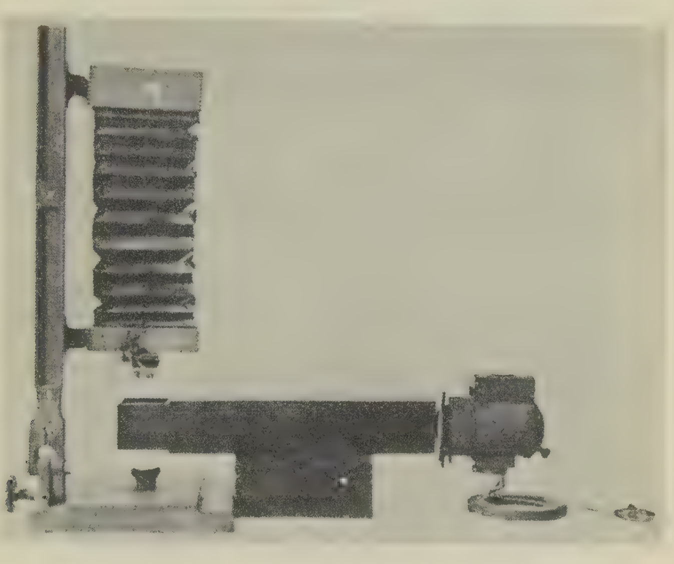

FIG. 2. Illuminator set up with camera, lighting equipment, and specimen.

The light source is a Spencer Microscope Lamp (No. 370) equipped with a projection bulb and a daylight diffusing screen which is mounted on the lamp and swings in or out in front of the bulb. A ground glass plate about 2 inches from the reflecting plate equalizes the illumination.

The camera has ground glass focusing equipment and a long extension bellows. The image can be projected on the ground glass to give an approximate focus and to outline the image as it will appear on the plate. For a final focus a transparent glass and a large focusing lens is necessary.[1]

The camera lens used by the writer is a 12 cm. Leitz photographic lens. A shorter focal length is not recommended. A longer focal length would probably be more satisfactory, for in that case for a given magnification the lens would be farther from the specimen. The cone of light from the specimen would be narrower and the light received would be more nearly vertical.

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[1] Short, M. N., Microscopic Determination of the Ore Minerals: *U. S. Geol. Survey, Bull.* **825,** 20 (1931).

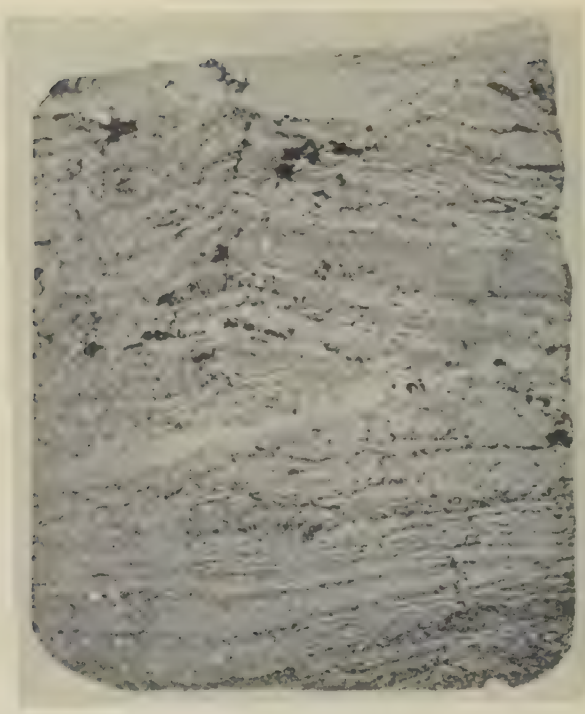

Fig. 3. Disseminated grains of pyrite and chalcopyrite in schist. Magnification 2×. Oblique illumination will not bring out the disseminated grains, but by the use of vertical illumination the grains clearly stand out and their distribution over a rather large area is revealed.

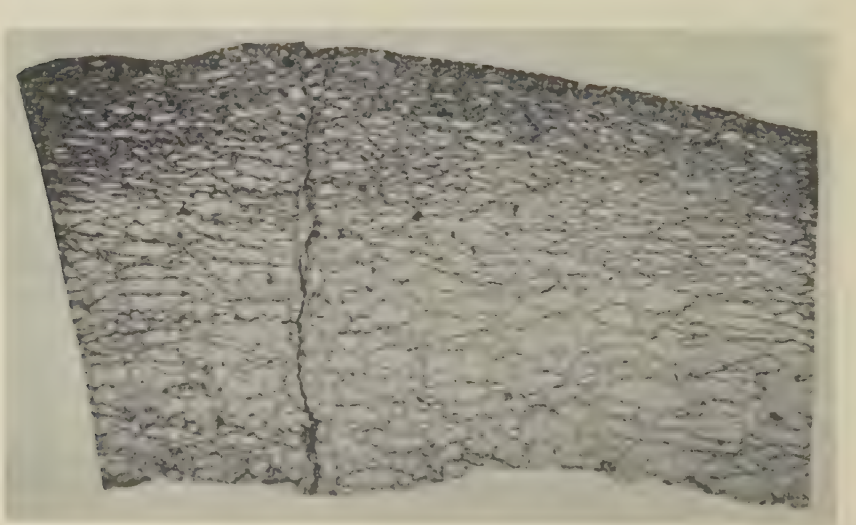

Fig. 4. Polished section of pyrite showing progressive replacement by chalcocite. Magnification 2×. This photograph illustrates a textural gradation which could not be fully illustrated by the limited field of the microscope.

A small stop on the camera lens increases the sharpness of the image. A stop of U. S. 24 is satisfactory as it gives a sufficient depth of focus for sharp images and exposure times are not excessive. Because the exposures are time exposures, the camera must be mounted on a firm foundation. Exposures vary with the specimen and it may be desirable to make a test strip for each photograph.

This illuminator was designed for mounted polished sections, but larger polished surfaces could be photographed by a correspondingly larger illuminator.

BOOK REVIEW

MANUAL OF SEDIMENTARY PETROGRAPHY. By W. C. KRUMBEIN AND F. J. PETTIJOHN. D. Appleton-Century Company, *New York.* 1939. XIV+549 pages. Price $6.50.

The book is divided into two parts. Part I, written by the senior author, embraces 10 chapters covering 274 pages. This section is devoted to a discussion of the following topics: collection and preparation of samples, mechanical analysis, graphic presentation of analytical data and statistical and orientation analysis of sedimentary particles.

Eleven chapters comprise Part II by the junior author. Here shape analysis, mineralogical and chemical analysis and mass properties are treated in considerable detail. The optical properties of about 55 minerals are listed and their appearance and relief expressed in line drawings as seen in a balsam mount.

The book summarizes the techniques, information and data that have appeared in widely scattered journals, many outside the field of geology proper. Those students who are mathematically inclined will find that this and the theoretical phases have not been overlooked. It is the first comprehensive American book in this field and the soil geologist and sedimentary petrologist will find it an extremely useful text.

W. F. H.

PROCEEDINGS OF SOCIETIES

NEW YORK MINERALOGICAL CLUB, INC.

The American Museum of Natural History, New York City
Meeting of March 15, 1939

The meeting was called to order by First Vice-President Lee at 8:10 P.M., with 67 members and guests present. Announcement was made of the Spring Excursion to Trumbull, Connecticut, to take place in May.

The speaker of the evening, Dr. Frank Schairer of the Geophysical Laboratory of the Carnegie Institution of Washington, was then introduced. He spoke to the members upon the minerals of "The Pyroxene Family." In this talk he traced the work of the Geophysical Laboratory and the problems which are facing them in the final solution of the pyroxene series. After some discussion the meeting was adjourned for the examination of typical specimens brought by Dr. Schairer from the United States National Museum to illustrate his talk.

F. H. POUGH, *Secretary*

NEW YORK MINERALOGICAL CLUB, INC.

The American Museum of Natural History, New York City
Meeting of April 19, 1939

The meeting was called to order by First Vice-President Lee at 8:15 P.M. with 75 members and guests present. Announcement was made of the Spring Excursion to Long Hill, Trumbull, Conn., on May 7th. The election of officers for the next year followed. They are:

President: Harry R. Lee.
First Vice-President: O. Ivan Lee.
Second Vice-President: James F. Morton.
Secretary: Frederick H. Pough.

Treasurer: James A. Taylor.
Director: Gilman S. Stanton

The speaker, Mr. Samuel G. Gordon of the Philadelphia Academy of Natural Sciences, was then introduced. He told the members of his collecting trip in Peru and Chile in search of minerals. Mr. Gordon travelled on a specially designed motor-cycle over the cart roads of the Atacama Desert, visiting nitrate and copper mines. He was well rewarded by many fine specimens, some of which were shown to the members after the talk. He emphasized the size of the copper mine at Chuquicamata and said that until now no real collecting had been done at the locality. Sierra Gorda was another locality which had been neglected, but it is now too late, as most of the mines are closed. However, the reserves at Chuquicamata are so enormous that many fine minerals can still be found there. The meeting adjourned at 9:45 to examine the specimens.

F. H. Pough, *Secretary*

NEW HAVEN MINERAL CLUB

The New Haven Mineral Club has just completed its sixth season. At the October meeting Charles Thomas of Wallingford was elected President; Frederick Fowler of New Haven, Vice-President, Lillian M. Otersen of West Haven, Secretary, and Sadie Crowley of New Haven, Treasurer.

At the October meeting the members displayed the best specimens they had collected the preceding summer and made plans for the winter speakers. In November the Program Committee invited Stephen Varni who gave an illustrated talk on various outstanding gems and displayed some fine gems and mineral specimens. At the December meeting the club had the pleasure of hearing John Grenzig of Brooklyn, New York, talk on his 50 years' experience collecting mineral oddities.

In January, Arthur Montgomery of New York City gave an illustrated lecture on his collecting in Alaska and the Western section of the United States. James Morton, Curator of the Paterson Museum, visited the club and gave his experiences in collecting at the zeolite localities in Nova Scotia and also at the famous Paterson Quarries.

In March Professor Daniel T. O'Connell of the City College of New York gave an illustrated lecture on the Grand Canyon and the geological story of this famous region.

At the last meeting of the year, April 10, the members were fortunate to see a professional lapidary at work. Mr. John Vlismas of New York City gave a demonstration of cutting and polishing, and finished two paper weights of onyx inlaid with malachite and Death Valley onyx.

The following summer outings have been arranged.

April 16, Morris Dam, Woodbury and Southbury will be visited where there is an abundance of smoky and rose quartz.

May 21, Tungsten Mine at Long Hill, where many fine specimens of fluorite, scheelite, topaz and the tungsten ores may be gathered.

June 18, Gillettes Quarry at Haddam Neck and Rock Landing, where specimens of gem quality tourmaline may be found.

July 16, Tilly Foster, serpentine location with clinochlore, brucite and many other fine minerals in abundance.

Aug. 20, Diamond Ledge, West Stafford, Conn., a famous quartz locality.

Sept. 17, Bedford, New York, one of the most famous feldspar quarries.

Oct. 15, Roxbury iron and garnet localities.

Lillian M. Otersen, *Secretary*

NEW MINERAL NAMES

Kotoite

Takeo Watanabe: Kotoite, ein neues gesteinsbildendes Magnesiumborat. *Mineral. Petro. Mitt.*, **50,** 411–643 (1939).

Name: In honor of the late Prof. Dr. Bundjirô Kotô, who first described the ore deposits of Hol Kol.

Chemical Properties: A magnesium borate: $Mg_3B_2O_6$. Analysis: SiO_2 1.32; Al_2O_3 0.26; FeO 0.61; Fe_2O_3 0.20; CaO 0.18; MgO 62.78; B_2O_3 35.20; $H_2O+110°$ 0.05; sum 100.60. Soluble in warm concentrated hydrochloric acid; scarcely attacked by cold dilute acid; the solution reacts for Fe, Mg and B. B.B. infusible.

Crystallographical Properties: Crystals not observed. Orthorhombic.

Physical and Optical Properties: Colorless. $H=6\frac{1}{2}$. $G=3.06–3.11$. Cleavage fairly good (110), simple gliding along (101). Biaxial (+). $2V=21\ \pm 1$. $r>v$, plane of the optic axes (010). $Z=c$. $\alpha=1.652$, $\beta=1.653$, $\gamma=1.673$.

Occurrence: Found in metamorphosed dolomitized marble, associated with fosterite, norbergite, spinel, ludwigite, szaibelyite, fluoborite, etc., at Hol Kol gold mine, Suan Korea and Rezbanya, Siebenbürgen.

W. F. Foshag

Verdelite

P. Quensel and O. Gabrielson: Minerals of the Varuträsk Pegmatite. XIV. The Tourmaline Group. *Geol. Fören. Förh. Stockholm*, **61,** 67 (1939).

The varietal name *verdelite* is proposed for the green lithium tourmaline to distinguish it from achroite (colorless), rubellite (red), indicolite (blue).

W. F. F.

Devadite

L. L. Fermor: Notes on Vredenburgite (with Devadite) and on Sitaparite. *Proc. Nat. Inst. Sci., India*, **4,** No. 3, 253–288 (1938).

Fermor reviews the previous work on vredenburgite which showed it to be an oriented intergrowth of jacobsite and hausmanite that has resulted from the breakdown of a preexisting mineral. For this presumed earlier mineral, near $3Mn_3O_4$, $2Fe_2O_3$, in composition, Fermor retains the name vredenburgite, and for a similar hypothetical mineral, richer in iron, from which has presumably been derived the "vredenburgite" of Devada and Kodur, the name *devadite* is proposed.

W. F. F.